



## Physics at the 100km Future Circular Collider (FCC-ee): From precision measurements to right-handed neutrinos

<http://cern.ch/fcc-ee> → Can subscribe to receive news, invitations etc...

Many thanks to the FCC-ee *very international* design study group!



Physics at FCC-ee

Alain Blondel, University of Geneva

Wine and Cheese seminar, Fermilab, 10 June 2016



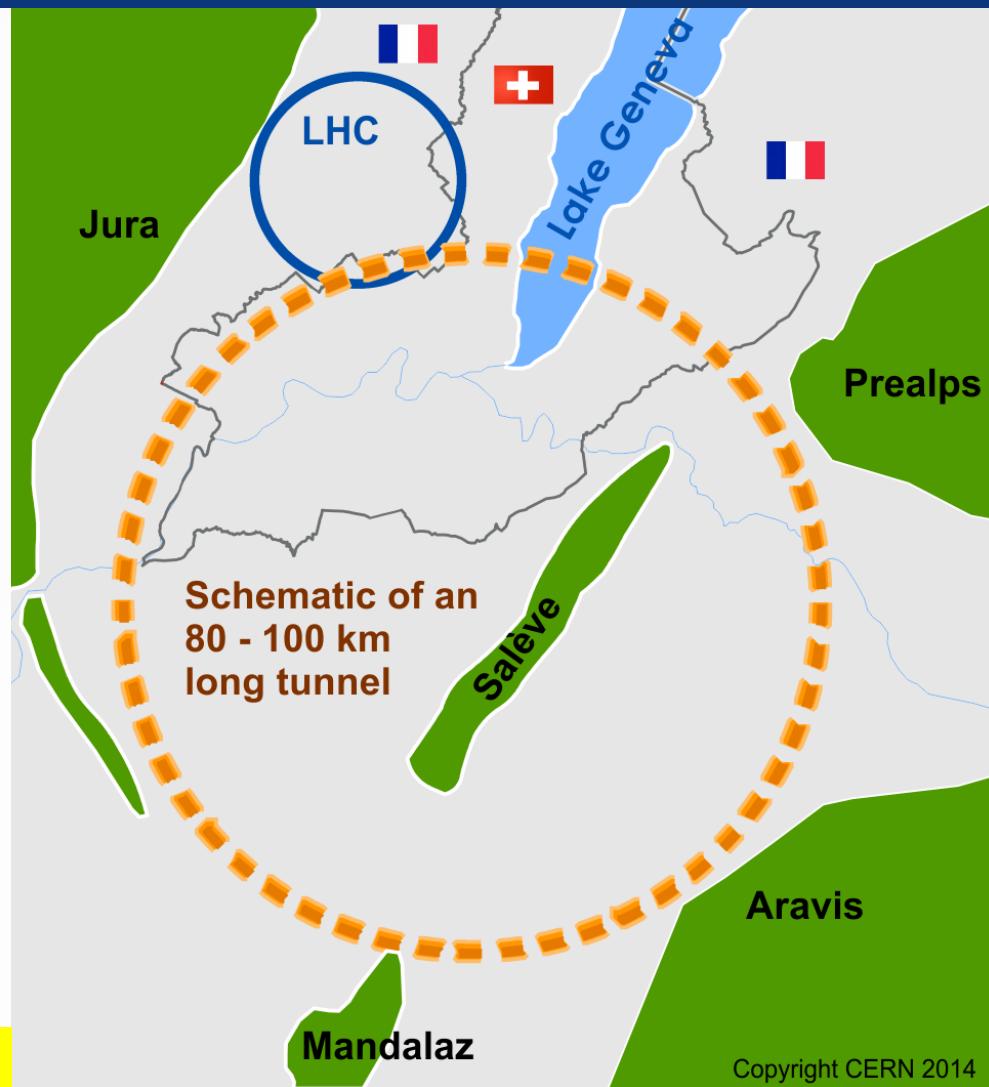
# Future Circular Collider Study

**GOAL: CDR and cost review for the next ESU (2019)**

International FCC collaboration  
(CERN as host lab) to study:

- **$pp$ -collider  $O(100)$  TeV (FCC-*hh*)**  
→ main emphasis, defining infrastructure requirements
- **$\sim 16$  T    100 TeV  $pp$  in 100 km**
- **80-100 km tunnel infrastructure** in Geneva area
- **$e^+e^-$  collider (FCC-*ee*) 90-400GeV as possible first step**
- **$p-e$  (FCC-*he*) option**
- **HE-LHC with FCC-*hh* technology**

M. Benedikt



Physics at FCC-*ee*

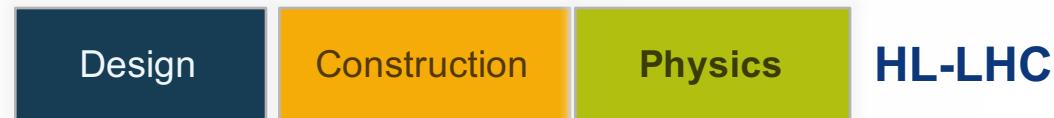
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# CERN Circular Colliders and FCC



*Notional time line:*



M. Benedikt

FCC

Design

Proto

Construction

Physics

**Now is the right time to plan for the period 2035 – 2040**

(FCC-ee)

**Goal of phase 1: CDR by end 2018 for next update of European Strategy**



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# progress on site investigations



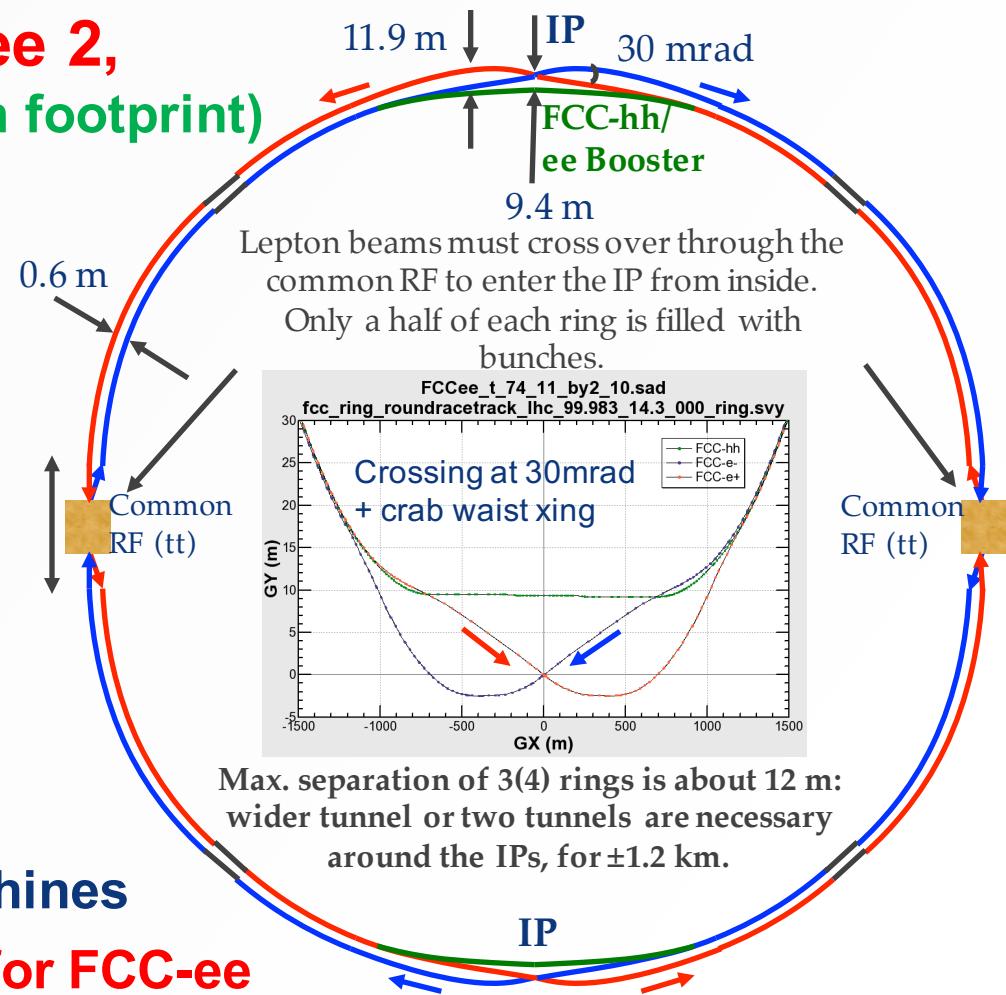
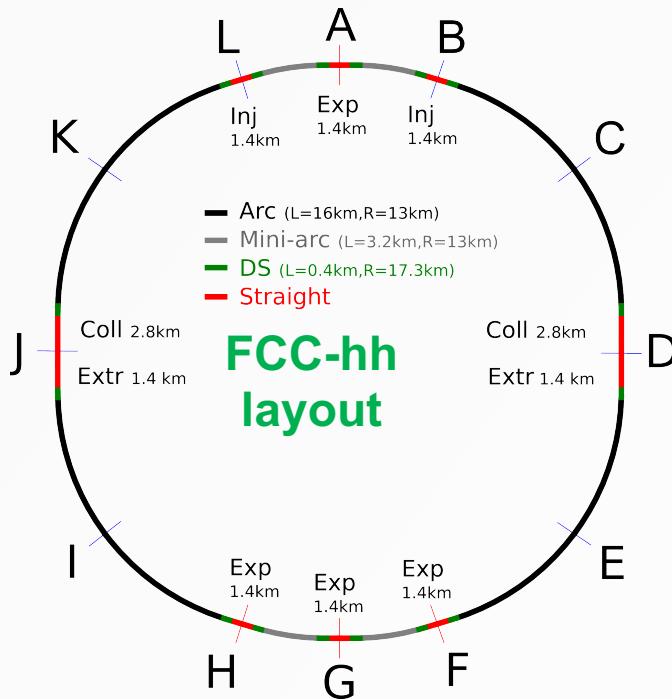
- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is now being studied in more detail

J. Osborne, C. Cook



# common layouts for hh & ee

**FCC-ee 1, FCC-ee 2,  
FCC-ee booster (FCC-hh footprint)**



- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for FCC-ee limits synchrotron radiation to detector to <100keV**

K. Oide, D. Schulte,  
A. Bogomyagkov,  
B. Holzer, et al.



A. Blondel, J. Ellis, C. Grojean, P. Janot

## □ **physics programs / energies:**

**Z (45.5 GeV) Z pole**, ‘TeraZ’ and high precision  $M_Z$  &  $\Gamma_Z$

**W (80 GeV) W pair production** threshold, high precision  $M_W$

**H (120 GeV) ZH production** (maximum rate of H’s)

**t (175 GeV): t $\bar{t}$  threshold**, H studies

□ **beam energy range from 40 GeV to  $\approx 190$  GeV**

□ **highest possible luminosities** at all working points

□ **possibly H (63 GeV) direct s-channel** production with  
monochromatization

(c.m. energy spread <6 MeV, presentation at IPAC’16)

□ **beam polarization up to  $\geq 80$  GeV** for beam energy calibration



# lepton collider parameters

| parameter  | FCC-ee |       |      |            | LEP2 |
|--|--------|-------|------|------------|------|
| physics working point                                      | Z      | WW    | ZH   | $t\bar{t}$ |      |
| energy/beam [GeV]  | 45.6   | 80    | 120  | 175        | 105  |
| bunches/beam   | 30180  | 91500 | 5260 | 780        | 81   |
| bunch spacing [ns]   | 7.5    | 2.5   | 50   | 400        | 4000 |
| bunch population [ $10^{11}$ ]                             | 1.0    | 0.33  | 0.6  | 0.8        | 1.7  |
| beam current [mA]  | 1450   | 1450  | 152  | 30         | 6.6  |
| luminosity/IP $\times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ | 210    | 90    | 19   | 5.1        | 1.3  |
| energy loss/turn [GeV]                                     | 0.03   | 0.03  | 0.33 | 1.67       | 7.55 |
| synchrotron power [MW]                                     | 100    |       |      |            |      |
| RF voltage [GV]  | 0.4    | 0.2   | 0.8  | 3.0        | 10   |
| rms cm $E$ spread SR [%]                                   | 0.03   | 0.03  | 0.05 | 0.07       | 0.10 |
| rms cm $E$ spread SR+BS [%]                                | 0.15   | 0.06  | 0.07 | 0.08       | 0.12 |



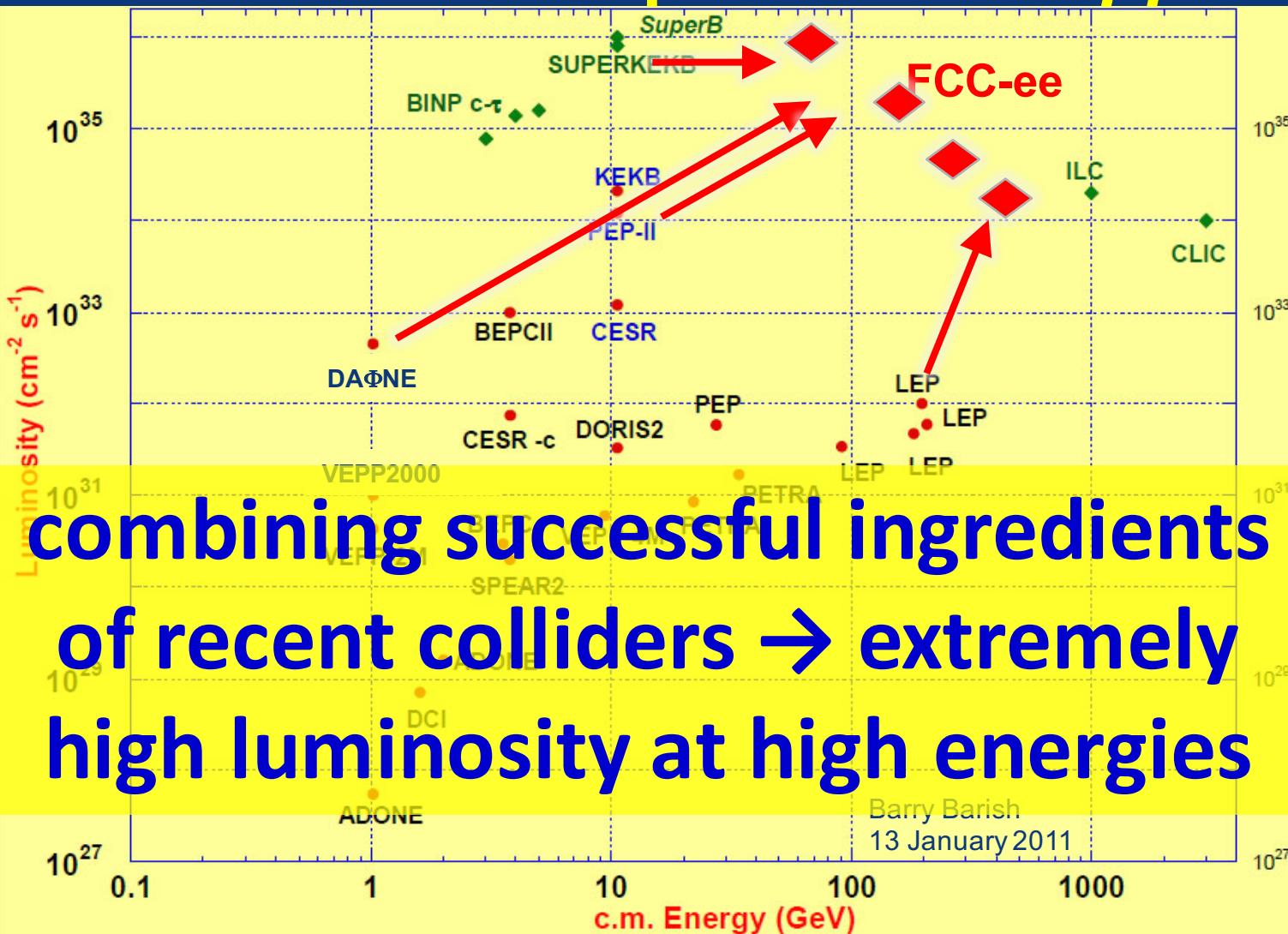
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# FCC-ee exploits lessons & recipes from past $e^+e^-$ and $pp$ colliders



**LEP:**  
high energy  
SR effects

**B-factories:**  
KEKB & PEP-II:  
high beam  
currents  
top-up injection

**DAΦNE:** crab waist

**Super B-factories**

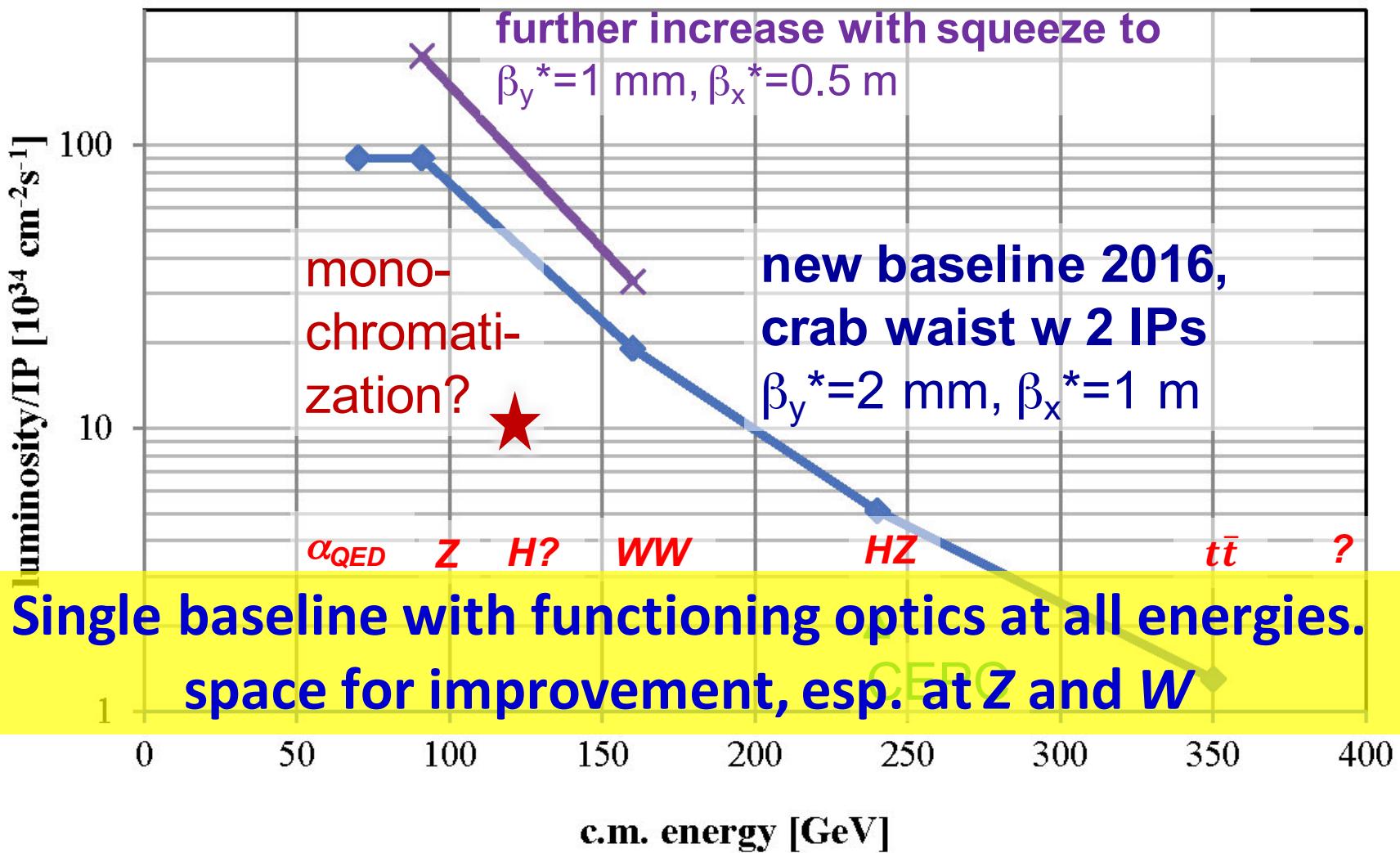
**S-KEKB:** low  $\beta_y^*$

**KEKB:**  $e^+$  source

**HERA, LEP, RHIC:**  
spin  
gymnastics



## FCC-ee luminosity per IP

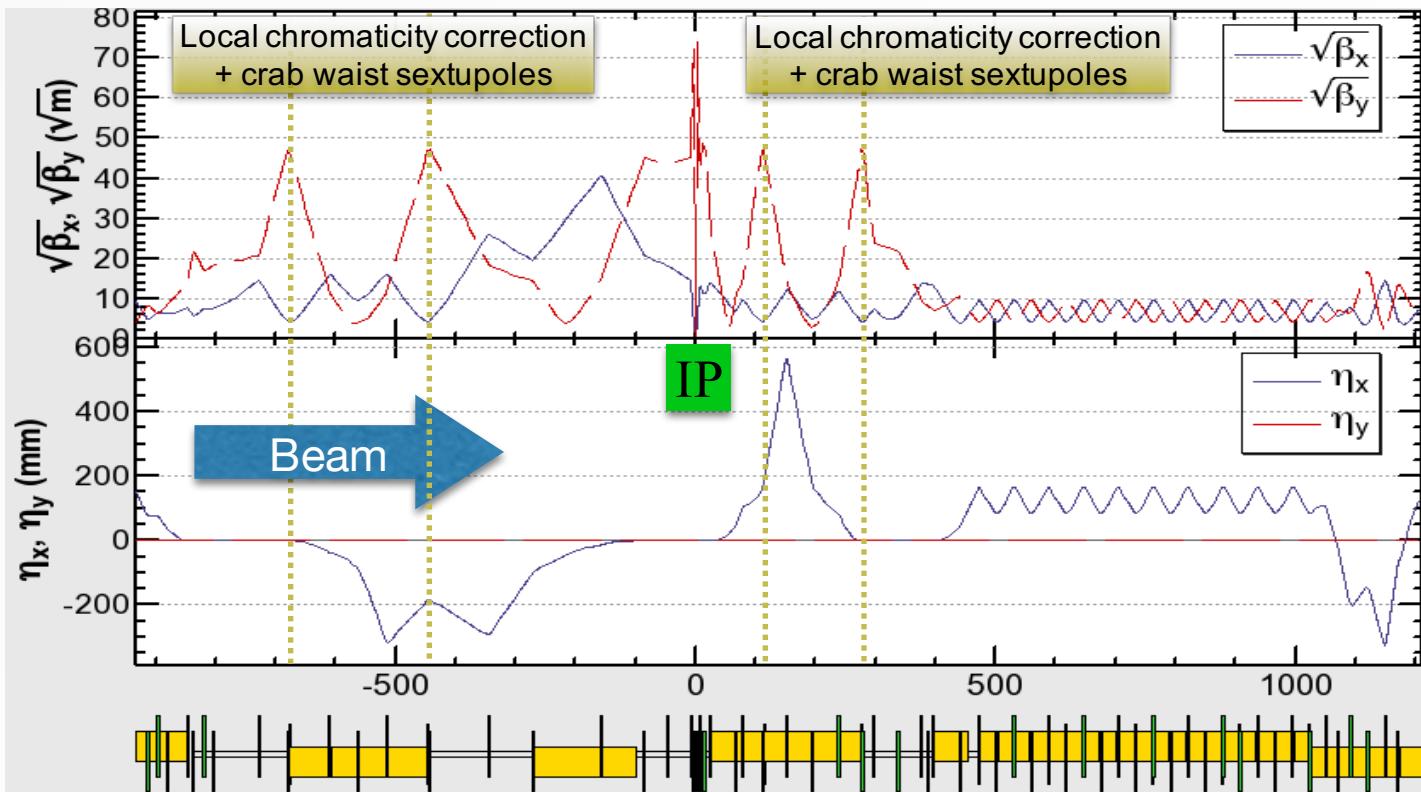


# FCC-ee optics design

**Optics design for all working points achieving baseline performance**

**Interaction region: asymmetric optics design**

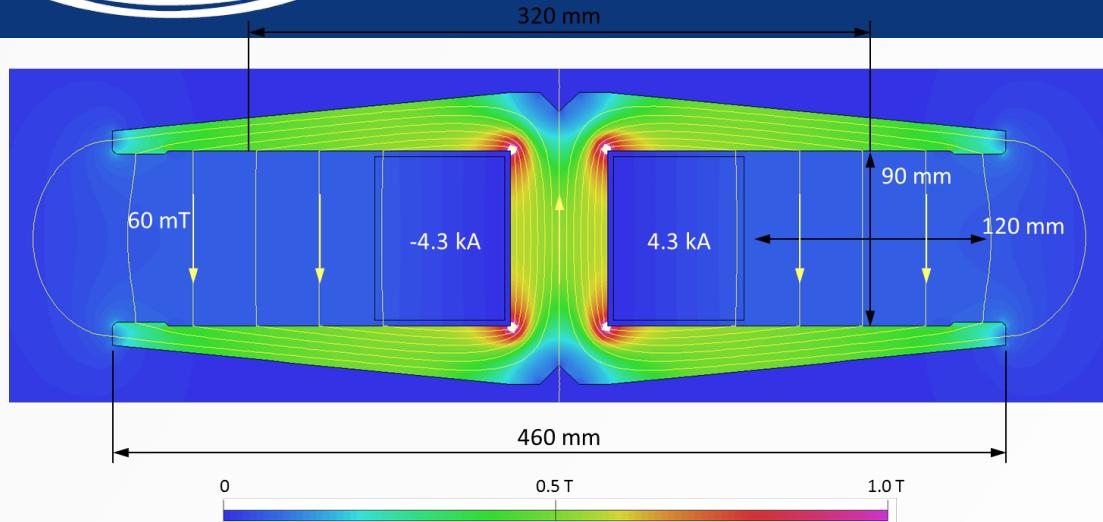
- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs



K. Oide



# efficient 2-in-1 arc magnets



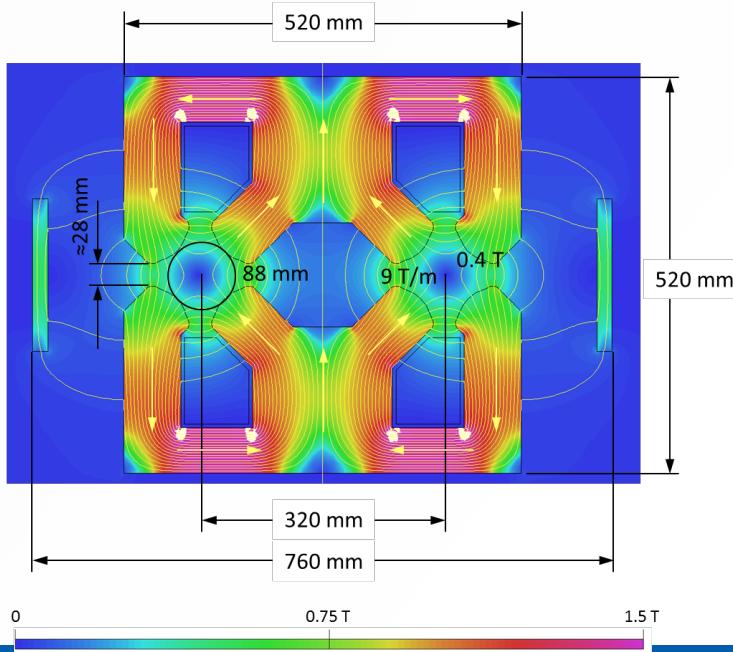
dipole based on twin aperture yoke and single busbars as coils

A. Milanese

## twin 2-in-1 quadrupole

the novel arrangements of the magnetic circuit allow for considerable savings in Ampere-turns and power consumption, less units to manufacture, transport, install, align, remove,...

midplane shield for stray field



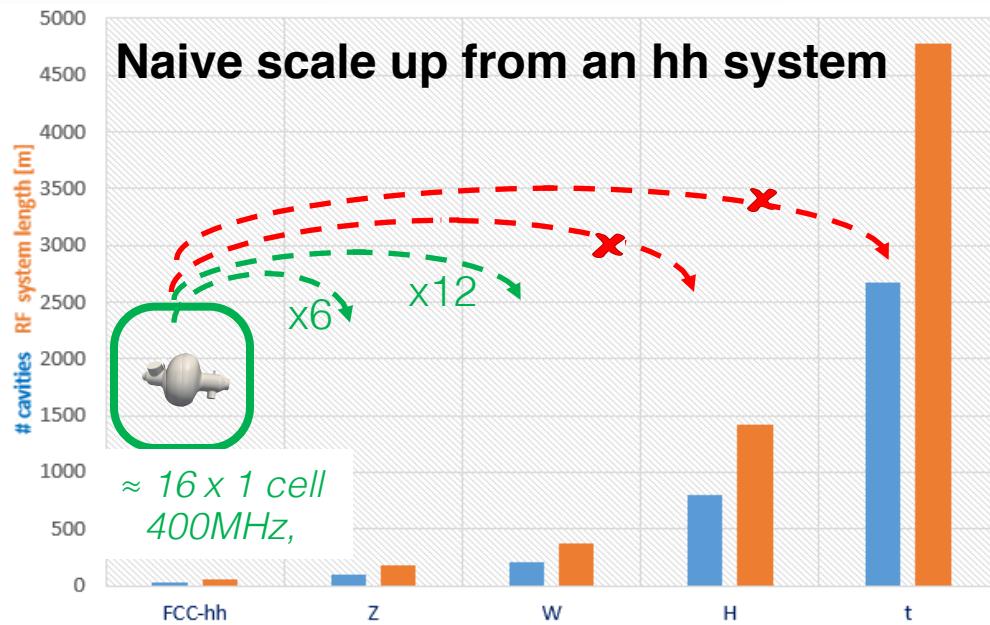
# RF system requirements

**Very large range of operation parameters**

**“Ampere-class” machines**

|        | V <sub>total</sub><br>GV | n <sub>bunches</sub> | I <sub>beam</sub><br>mA | ΔE/turn<br>GeV |
|--------|--------------------------|----------------------|-------------------------|----------------|
| FCC-hh | 0.032                    |                      | 500                     |                |
| Z      | 0.4/0.2                  | 30000/90000          | 1450                    | 0.034          |
| W      | 0.8                      | 5162                 | 152                     | 0.33           |
| H      | 5.5                      | 770                  | 30                      | 1.67           |
| t      | 10                       | 78                   | 6.6                     | 7.55           |

**“high gradient” machines**



- Voltage and beam current ranges span more than factor > 10<sup>2</sup>**
- No well-adapted single RF system solution satisfying requirements**

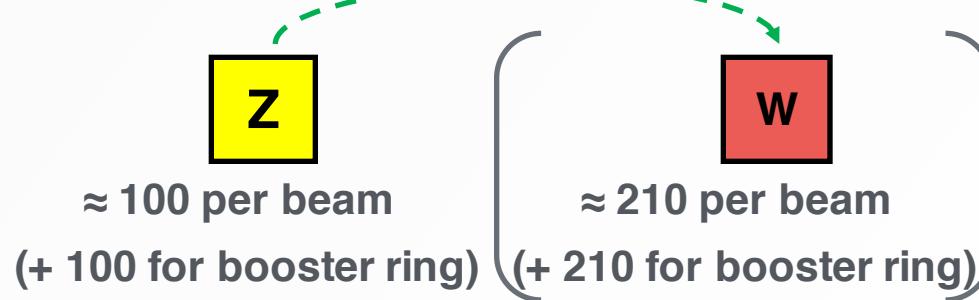
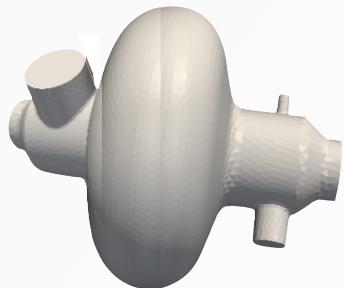
O. Brunner, A. Butterworth, R. Calaga,...



# RF system R&D lines

## 400 MHz single-cell cavities preferred for hh, ee-Z and ee-W (few MeV/m)

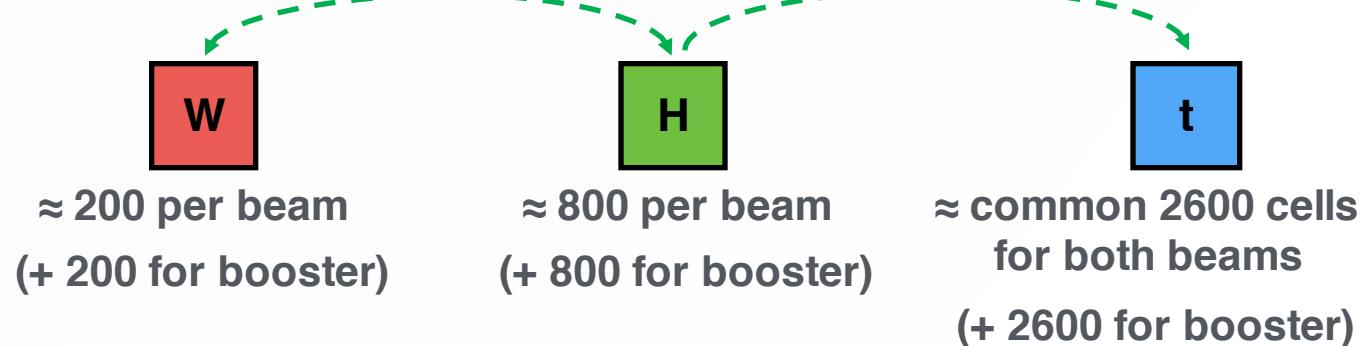
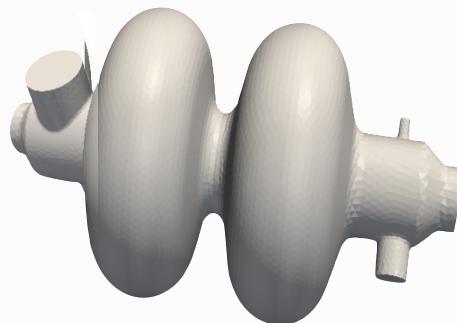
- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
  - R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)



**400 or 800 MHz multi-cell cavities preferred for ee-W, ee-ZH and ee-tt**

**baseline options 400 MHz Nb/Cu @4.5 K,  $\longleftrightarrow$  800 MHz bulk Nb system @2K**

- R&D: High  $Q_0$  cavities, coating, long-term: Nb<sub>3</sub>Sn like components



# highly efficient RF power sources

2014 breakthrough in klystron theory:

- “congregated bunch” V.A. Kochetova, 1981] (later electrons faster when entering the output cavity)

- “bunch core oscillations” [A. Yu. Baikov, et al.:

“Simulation of conditions for the maximal efficiency of decimeter-wave klystrons”, Technical Physics 2014] (controlled periodic velocity modulation)

- “BAC” method [I.A. Guzlov, O.Yu. Maslennikov, A.Y. Konnov, “A way to increase the efficiency of klystrons”, IVEC 2013] (Bunch, Align velocities, Collect outsiders)

**These three methods together promise a klystron efficiency ~90%**

An international collaboration “HEIKA” (CERN, ESS, SLAC, CEA, MFUA, Lancaster U, Thales, L3, CPI, VDBT) is now designing, building and testing prototypes at several places around the world.

**Simulations and first hardware tests extremely encouraging.**

For CW operation  
work in progress

FCC klystron prototype - initial target parameters

|                          |   |
|--------------------------|---|
| Operating frequency      | 800 MHz initially                               |
| Target RF Output power   | 1.5 MW (cw)                                     |
| Voltage                  | 40 kV   |
| N-beams×Current          | $16 \times 2.6 \text{ A} = 42 \text{ A}$        |
| <b>Target Efficiency</b> | <b>90%</b>                                      |
| Perveance                | $16 \times 0.33 \mu\text{K} = 5.25 \mu\text{K}$ |
| Number of cavities       | 8   |
| Cathode loading          | $< 2 \text{ A mm}^{-2}$                         |
| Length                   | 2.3 m   |



E. Jensen, I. Syratchev, C. Lingwood

Physics at FCC-ee

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Wine and Cheese seminar, Fermilab, 10 June 2016

# FCC-ee total power

| subsystem                | Z          | W          | ZH         | $t\bar{t}$ | LEP2<br>(av.2000*) | TLEPt $t\bar{t}$<br>* M. Ross | TLEPt $t\bar{t}$<br>** 2013 |
|--------------------------|------------|------------|------------|------------|--------------------|-------------------------------|-----------------------------|
| collider total RF power  | 163        | 163        | 145        | 145        | 42                 | 217                           | 185                         |
| collider cryogenics      | 2          | 5          | 23         | 39         | 18                 | 41                            | 34                          |
| collider magnets         | 3          | 10         | 23         | 50         | 16                 | 14                            | 14                          |
| booster RF + cryo        | 4          | 4          | 6          | 7          | 5                  | 5                             | 5                           |
| booster magnets          | 0          | 1          | 2          | 5          | -                  | -                             | -                           |
| injector complex         | 10         | 10         | 10         | 10         | <10                | ?                             | ?                           |
| physics detectors (2)    | 10         | 10         | 10         | 10         | 9                  | ?                             | ?                           |
| cooling & ventilation*** | 47         | 49         | 52         | 62         | 16                 | 62                            | 26                          |
| general services         | 36         | 36         | 36         | 36         | 9                  | 20                            | 20                          |
| <b>total</b>             | <b>275</b> | <b>288</b> | <b>308</b> | <b>364</b> | <b>120</b>         | <b>359</b>                    | <b>284</b>                  |

power roughly  $\propto$  luminosity

for comparison, total CERN complex in 1998 used up to 237 MW

\*M. Ross, ``Wall-Plug (AC) Power Consumption of a Very High Energy e+/e- Storage Ring Collider," 3 August 2013,  
<http://arxiv.org/pdf/1308.0735.pdf> ; \*\*M. Koratzinos et al., ``TLEP: A High-Performance Circular e+e- Collider to Study the Higgs Boson",  
 Proc. IPAC2013 Shanghai, 12--17 May 2013, <http://arxiv.org/pdf/1305.6498.pdf> 2013,

\*\*\* private discussions with M. Nonis

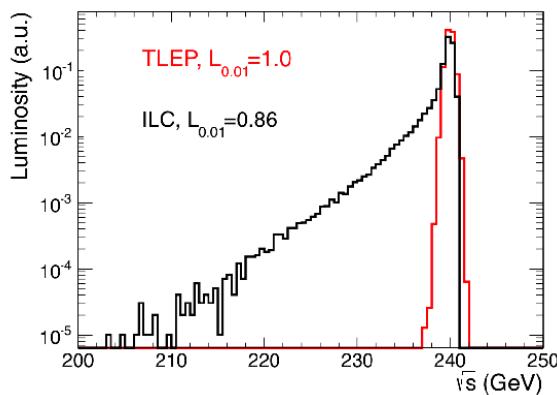
presentation at IPAC'16

\*dividing total energy used by 200 days



# Experimental conditions

- 2-4 IPs  $L^* \sim 2\text{m}$
- bunch crossing spacing from 2-5 ns (Z) up to 3 s (top)
- no pile-up (<0.001 at FCC-Z/CrabWaist)
- beamstrahlung is mild for experiments



|                   | FCCZ    | FCCZ, c.w | CEPC   | FCC ZH | ILC500 |
|-------------------|---------|-----------|--------|--------|--------|
| Npairs / BX       | 200     | 9900      | 3260   | 640    | 165000 |
| Leading process   | 96% LL  | 65% LL    | 80% LL | 90% LL | 60% BH |
| Epairs / BX (GeV) | 86      | 2940      | 2600   | 570    | 400000 |
| Leading process   | 100% LL | 100% LL   | 98% LL | 96% LL | 70% BH |

- Beam energy calibration for Z and W running
- IR design with crossing angle is not trivial  
→ a challenging magnet design issue.

E. Perez,  
C. Leonidopoulos

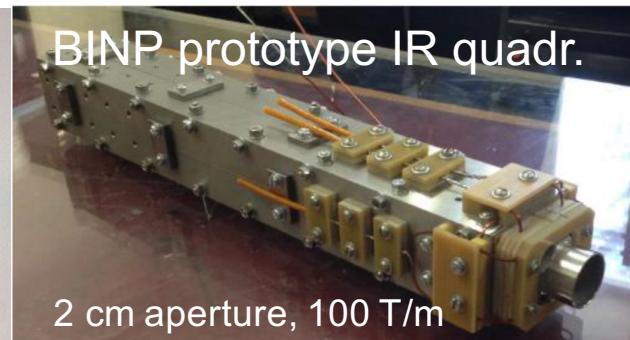
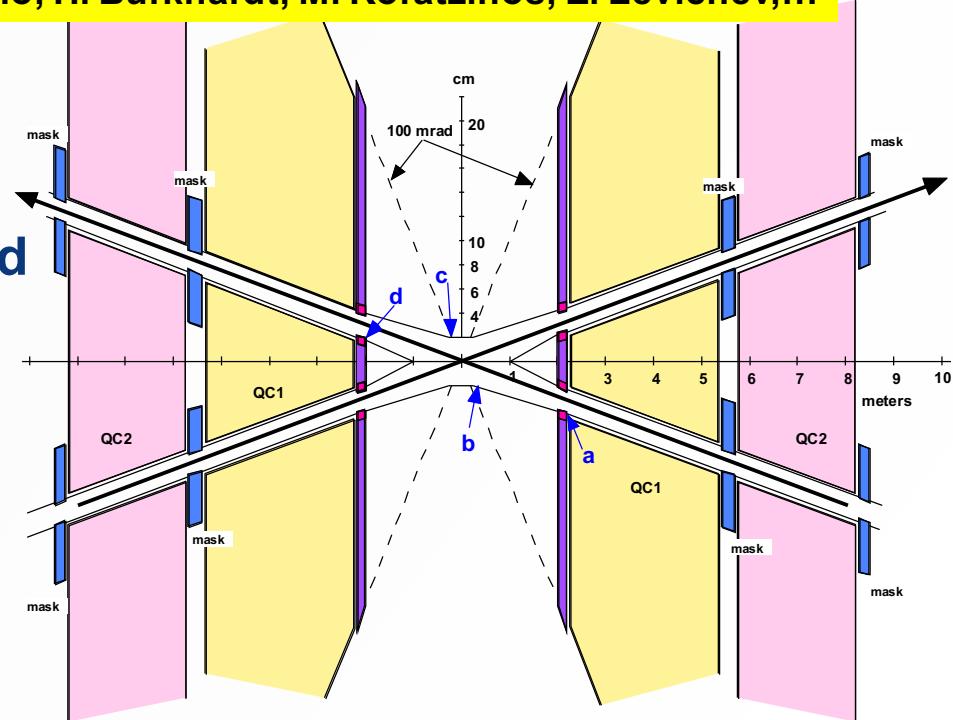
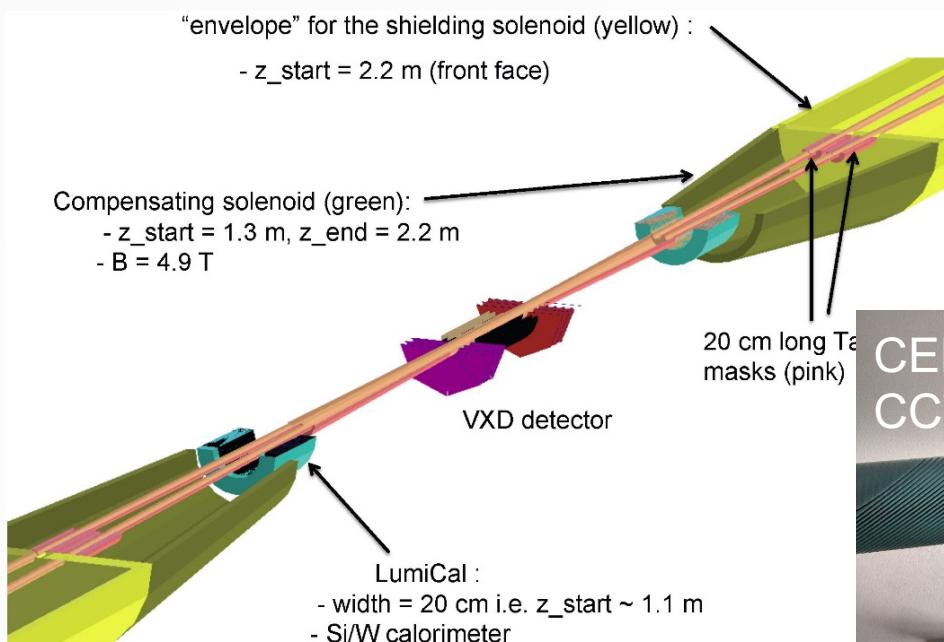


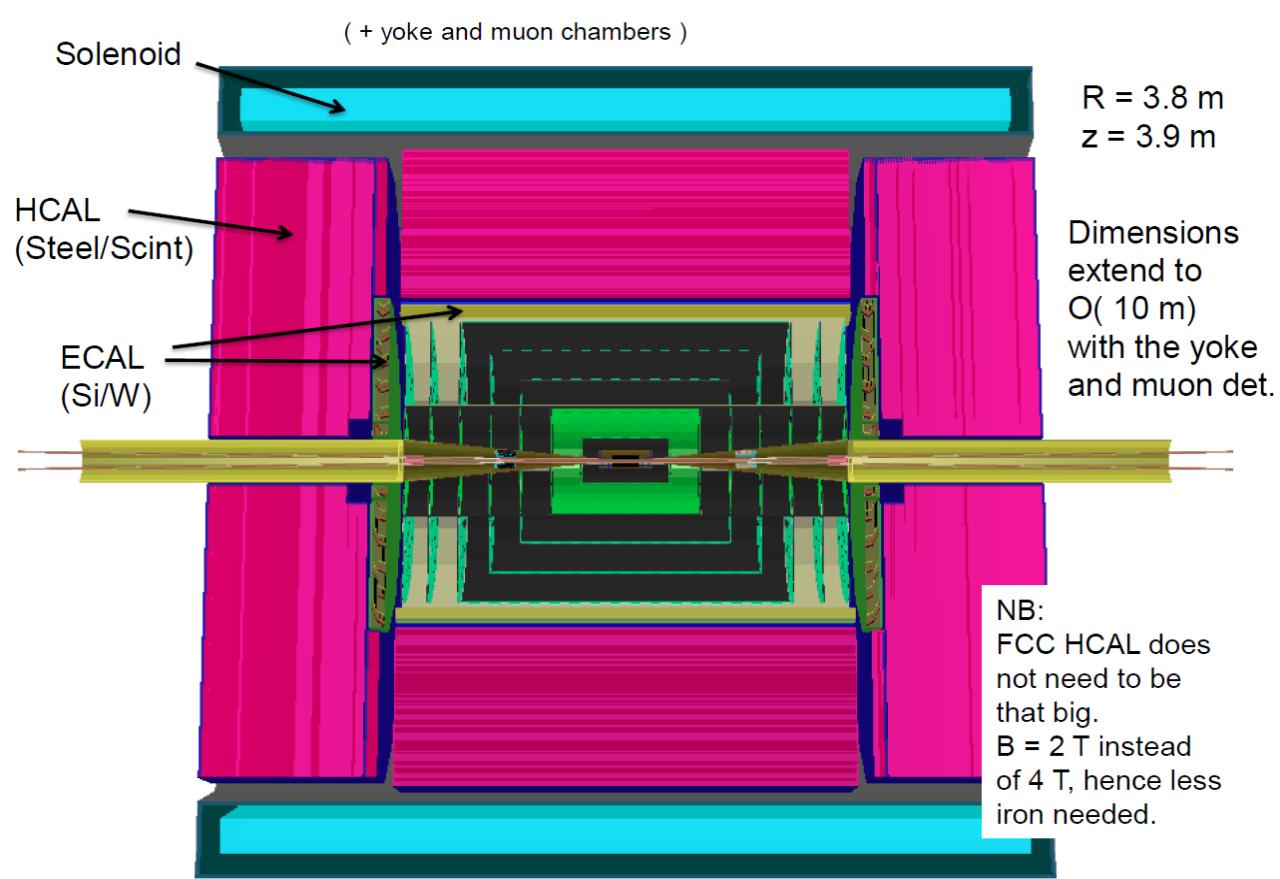
# FCC-ee MDI optimisation

M. Sullivan, E. Perez, M. Boscolo, H. Burkhardt, M. Koratzinos, E. Levichev,...

## MDI work focused on optimization of

- $I^*$ , IR quadrupole design
- compensation & shielding solenoid
- SR masking and chamber layout



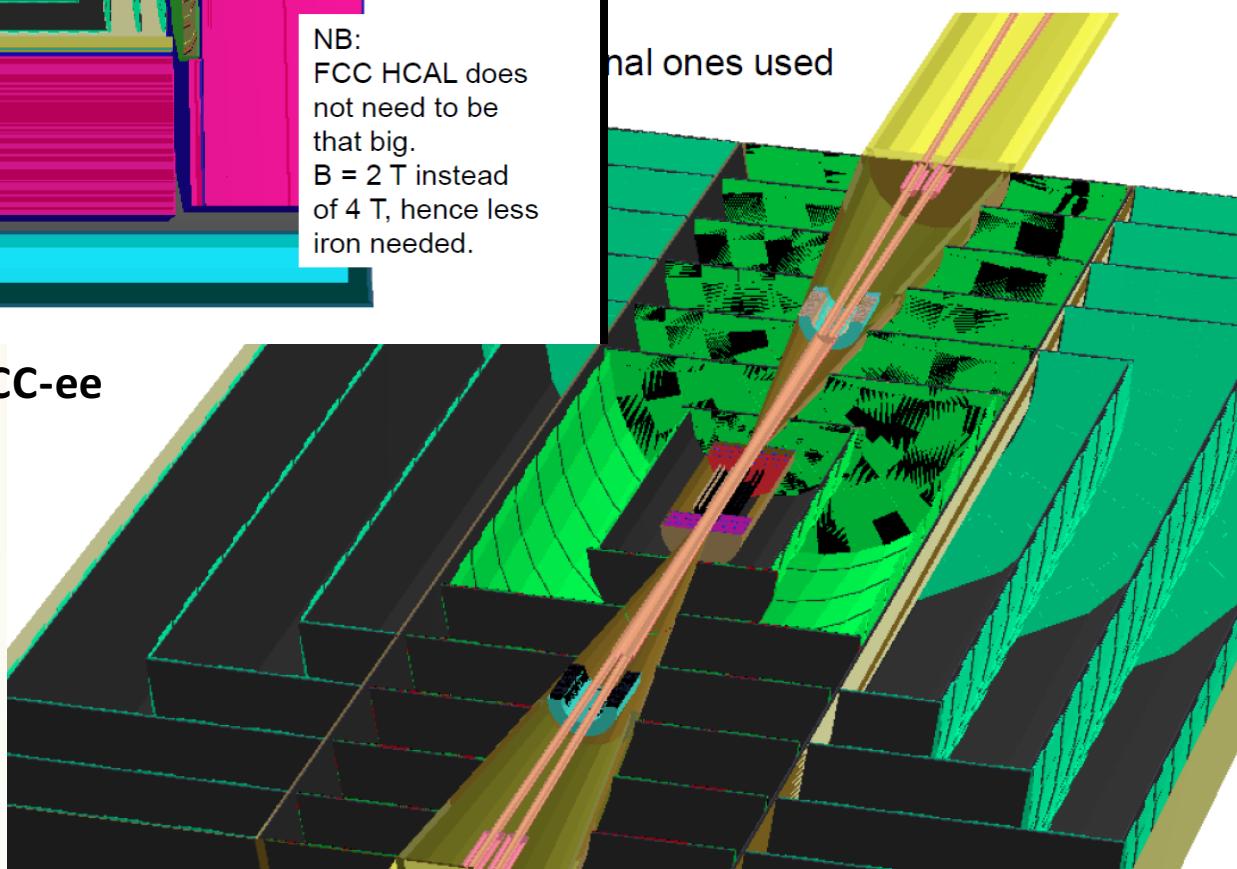


E. Perez

tracker

up to 100 mrad.

final ones used



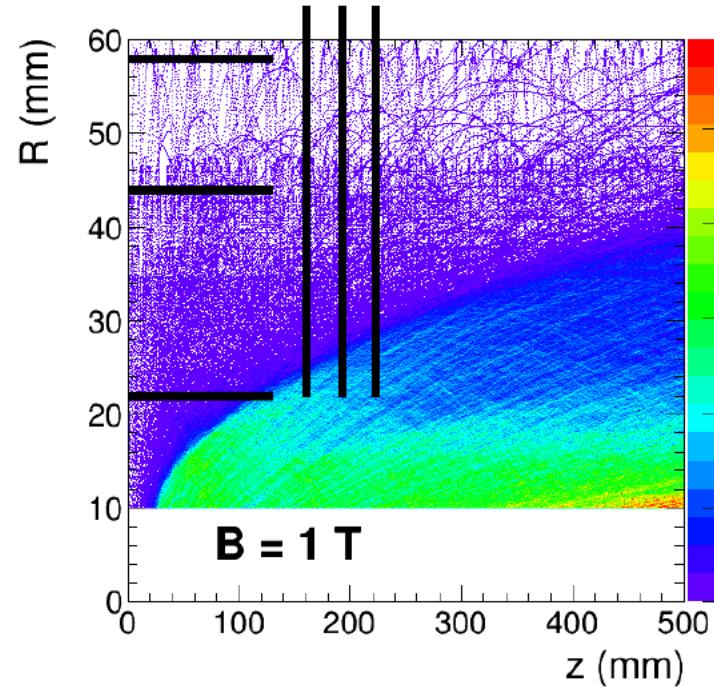
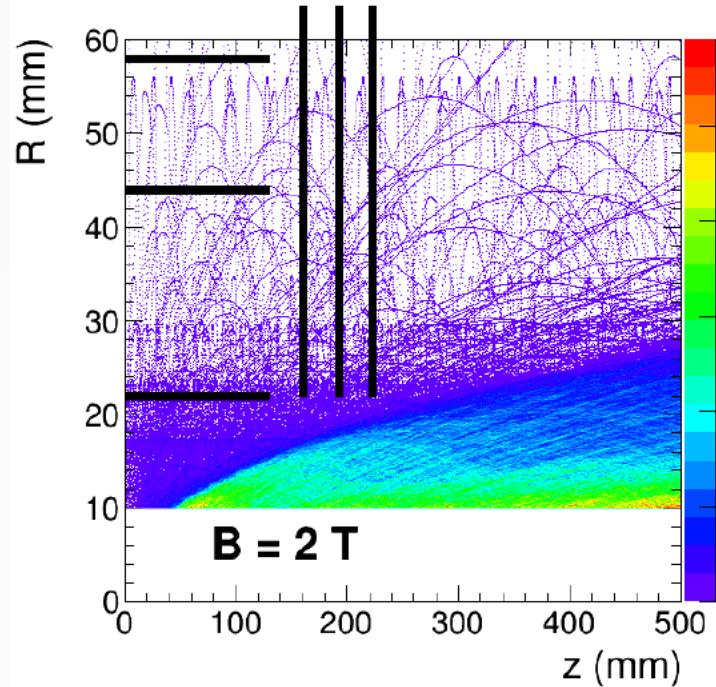
## Started adaption of CLIC det to FCC-ee

- will need to decrease B-field
- will need to reoptimize relative weight of tracker and calorimeter (physics, cost, and MDI)

# VTX detector can live at $\sim$ 2cm from IP.

Trajectories of  $e^+/-$  pairs in the 2T field

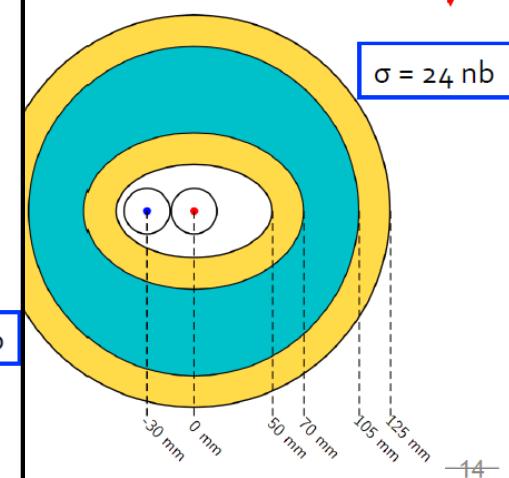
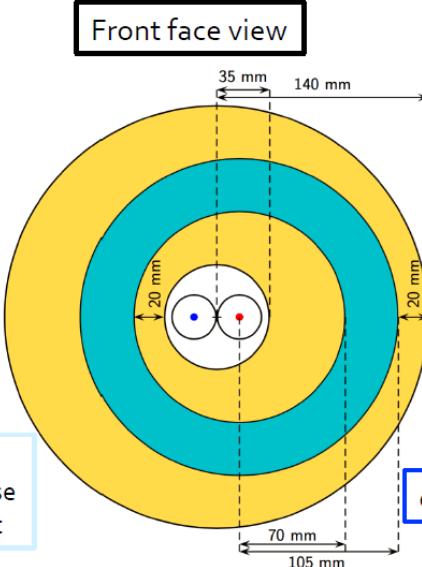
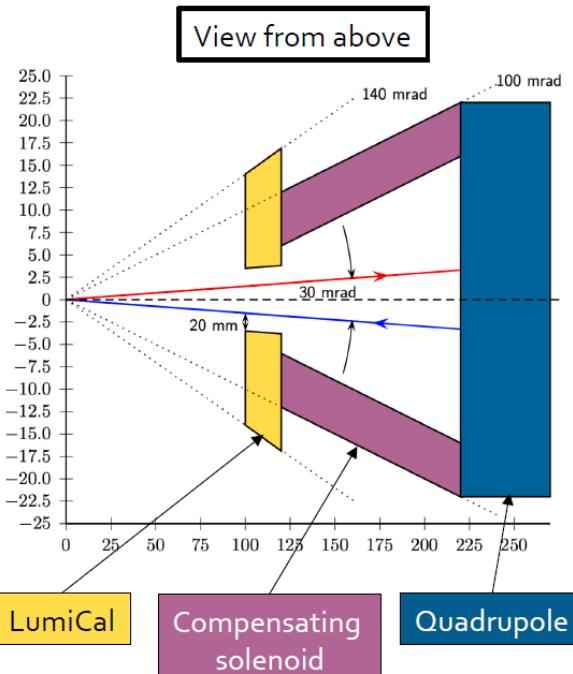
Helicoidal trajectories of the  $e^+/-$  pairs in the field of the experiment :



With the nominal value of  $B = 2\text{ T}$  and innermost layer of VXD at 2.2 cm :  
VXD avoids the hot region

- thanks to high luminosity can use two large angle QED processes  
 $e^+e^- \rightarrow$  and  $e^+e^- \rightarrow e^+e^-$
- need theoretical evaluation of  $e^+e^- \rightarrow$  @  $10^{-4}$  precision
- at and around Z pole need low angle Bhabha :

## Trying to squeeze in a LumiCal ...



Here, have assumed that compensating solenoid stops at  $z=120$  cm as proposed by M. Koratzinos

- Here
- Lumical centered in detector system
  - Tight acceptance centered around outgoing beam

# Beam polarization and E-calibration

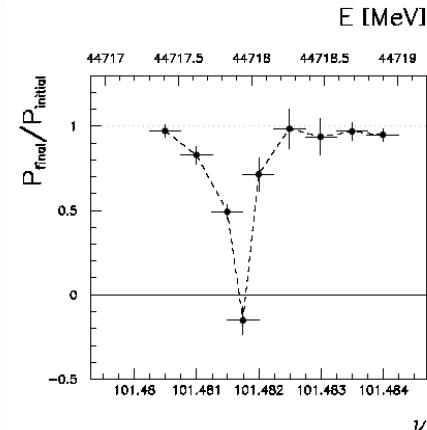
Precise meas of  $E_{beam}$  by resonant depolarization

$\sim 100 \text{ keV}$  each time the meas is made  $\rightarrow LEP \rightarrow$

At LEP transverse polarization was achieved routinely at Z peak.

*instrumental in  $10^{-3}$  measurement of the Z width in 1993*

*led to prediction of top quark mass ( $179 \pm 20 \text{ GeV}$ ) in March 94*



Polarization in collisions was observed ( $40\%$  at BBTS = 0.04)

At LEP a beam energy spread  $\frac{\delta E}{E} > 55 \text{ MeV}$  destroyed polarization above  $61 \text{ GeV}$   
 $\rightarrow$  At FCC-ee transverse polarization up to  $> 81 \text{ GeV}$  (WW threshold)

FCC-ee: use 'single' bunches to measure the beam energy continuously

*no interpolation errors due to tides, ground motion or trains etc...*

$\rightarrow$  further work is needed to understand operability

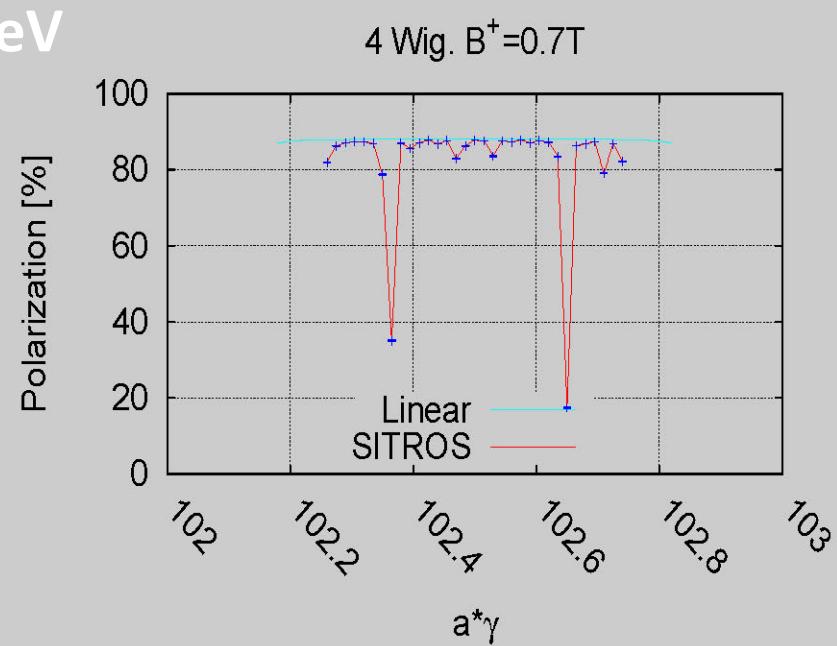
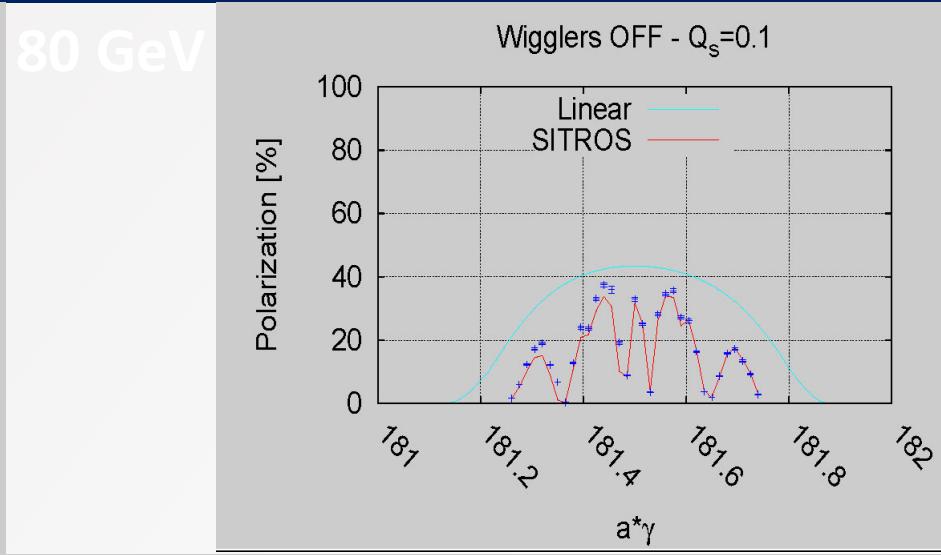
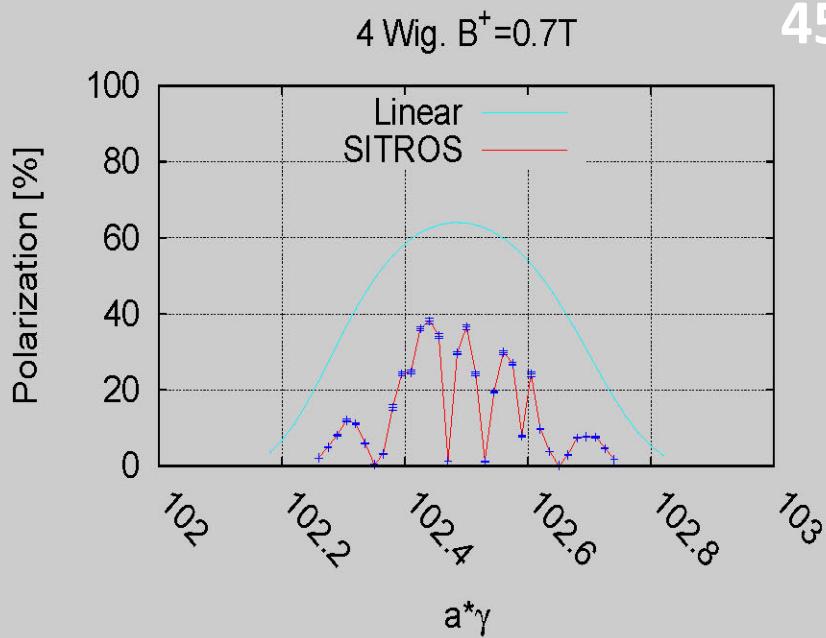
**<< 100 keV beam energy calibration around Z peak and W pair threshold.**

$m_Z \sim 0.1 \text{ MeV}$ ,  $Z \sim 0.1 \text{ MeV}$ ,  $m_W \sim 0.5 \text{ MeV}$



# FCC-ee self polarization allows precise $E$ calibration

- 45 GeV - goal  $E_{CM}$  calibration: 100 keV
  - limit  $\Delta E = 50$  MeV (extrapolating from LEP)
  - 4 wigglers with  $B^+ = 0.7$  T
  - 10% polarization in 2.9 h for energy calibration
- 80 GeV
  - no wigglers
  - 10% polarization in 1.6 h for energy calibration
- BPMs errors added to quadrupole misalignments



# estimated annual luminosity

assumptions:

- **160 days of physics per year**
- **two interaction points,**
- **“Hübner factor”=0.65 w top up inj. (KEKB, PEP-II)**

| mode                                | int. luminosity at two IPs   |                              |
|-------------------------------------|--|------------------------------|
| Z (91 GeV)                          | 17-40 ab <sup>-1</sup> / year                                      |                              |
| W (160 GeV)                         | 4 ab <sup>-1</sup> / year  |                              |
| ZH (240 GeV)                        | 1 ab <sup>-1</sup> / year  |                              |
| t <bar>t</bar>                      | (350 GeV)  | 0.25 ab <sup>-1</sup> / year |
| H (125 GeV) with monochromatization | >2 ab <sup>-1</sup> / year<br><i>preliminary, work in progress</i> |                              |





# typical running scenario

**Z pole:**  $1-2 \cdot 10^{36} \text{ cm}^2/\text{s/IP}$  →  $2.5 \cdot 10^{12} Z$  events (per experiment)      3-5 years  
+  $Z$  scan      1 year

**WW threshold:**  $3.5 \cdot 10^{35} \text{ cm}^2/\text{s/IP}$       1 year

$m_Z$ ,  $\alpha_Z(100 \text{ KeV})$ ,  $m_W(500 \text{ keV})$ ,  $\sin^2 \alpha_w^{\text{eff}}$  ( $< 10^{-5}$  from asymmetries & tau polar.),  
 $R_b$ , QED ( $m_Z$ ) ( $3 \cdot 10^{-5}$ ),  $\alpha_s(m_Z)$  ( $O(10^{-4})$  from  $B_{zh}$  &  $B_{wh}$ ),  $N_v$  from  $Z$  (0.0004) etc...

**ZH threshold** :  $5 \cdot 10^{34} \text{ cm}^2/\text{s/IP}$  :  $> 500'000$  Higgs / exp      4 years

**tt (E<sub>CM</sub> 350-365 GeV)**  $1.3 \cdot 10^{34} \text{ cm}^2/\text{s/IP}$       4 years

Higgs width ( $< 1\%$ ), invisible width ( $< 0.2\%$ ),  $HZZ$  ( $< 0.1\%$ ) etc. etc.

Top quark mass ( $O(10 \text{ MeV})$ ) and top couplings from top cross-section and polarization

above luminosities according to March 2016 baseline (with room for improvement);  
optimization will continue as luminosity figures evolve; there is no pile-up at FCC-ee!  
in addition possible run at  $e^+e^- \rightarrow H$  (125.2 GeV)





# FCC-ee discovery potential

*of course discovery depends on the goodwill of nature;  
a few things that FCC-ee could do and discover (if they exist):*

**EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements**

~20-50 fold improved precision on many EW quantities (eq. factor 5-7 in mass)  
 $m_Z$ ,  $m_W$ ,  $m_{top}$ ,  $\sin^2 \theta_w^{eff}$ ,  $R_b$ , QED ( $m_z$ ),  $s(m_z)$ , Higgs and top couplings

**DISCOVER that SM does not fit  $\rightarrow$  for sure exist extra ~weakly coupled particle(s)**

**DISCOVER a violation of flavour conservation**

- ex FCNC ( $Z \rightarrow \ell^+ \ell^-$ ,  $e^+ e^-$ ) in  $5 \cdot 10^{12}$   $Z$  decays.  
+ flavour physics ( $10^{12}$   $bb$  events!)

M. Bicer et al.,  
“First Look at the  
Physics Case of TLEP,”  
JHEP01 (2014) 164

**DISCOVER dark matter as «invisible decay» of  $H$  or  $Z$**

**DISCOVER very weakly coupled particle in 5-100 GeV energy scale  
such as: right-handed neutrinos, dark photons etc...**

.....

A. Blondel



Physics at FCC-ee

Alain Blondel, University of Geneva

Wine and Cheese seminar, Fermilab, 10 June 2016



# Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)  
no pile up, even at the Z: at most 1ev /300bx

## 1. Do we need polarized beams?

### -1- transverse polarization:

continuous beam Energy calibration with resonant depolarization  
central to the precision measurements of  $m_Z$ ,  $m_W$ ,  $\gamma$   
requires 'single bunches' and calibration of both e+ and e-  
a priori doable up to W energies -- workarounds exist above (e.g. Z events)  
large ring with small emittance excellent. Saw-tooth smaller than LEP for Z  
need wigglers (or else inject polarized e- and e+) to polarize 'singles';  
simulations ongoing (E. Gianfelice, M. Koratzinos, I.Kopp)

### -2- longitudinal polarization requires spin rotators and is very difficult at high energies

- We recently found that it is not necessary to extract top couplings (Janot)
- improves Z peak measurements *if loss in luminosity is not too strong*  
but brings no information that is not otherwise accessible
- because of top-up what is achievable is about 30% polarization for 1/20 luminosity@Z.

## 2. What energies are necessary?

- in addition to Z, W, H and top listed the following are being considered
  - $e^+e^- \rightarrow H(125.2)$  (requires monochromatization A. Faus) (under study)
  - $e^+e^-$  at top threshold + ~20 GeV for top couplings (E\_max up to 180 -185 GeV)
  - but no obvious case for going to 500 GeV



# A Sample of Essential Quantities:

| X                               | Physics                          | Present precision         |                        | TLEP stat<br>Syst Precision                           | TLEP key                   | Challenge                              |
|---------------------------------|----------------------------------|---------------------------|------------------------|---|----------------------------|--|
| $M_Z$<br>MeV/c <sup>2</sup>     | Input                            | 91187.5<br><b>2.1</b>     | Z Line shape scan      | <b>0.005 MeV</b><br><b>&lt; 0.1 MeV</b>               | E_cal                      | QED corrections                        |
| $z$<br>MeV/c <sup>2</sup>       | (T)<br>(no !)                    | 2495.2<br><b>2.3</b>      | Z Line shape scan      | <b>0.008 MeV</b><br><b>&lt; 0.1 MeV</b>               | E_cal                      | QED corrections                        |
| $R_I$                           | s, b                             | 20.767<br><b>0.025</b>    | Z Peak                 | <b>0.0001</b><br><b>0.0002</b>                        | Statistics                 | QED corrections                        |
| N                               | Unitarity of PMNS,<br>sterile 's | 2.984<br><b>0.008</b>     | Z Peak<br>Z+ (161 GeV) | <b>0.00008</b><br><b>0.004</b><br><b>0.0004-0.001</b> | ->lumi meast<br>Statistics | <b>QED corrections to Bhabha scat.</b> |
| $R_b$                           | b                                | 0.21629<br><b>0.00066</b> | Z Peak                 | <b>0.000003</b><br><b>0.000020 - 60</b>               | Statistics,<br>small IP    | Hemisphere correlations                |
| $A_{LR}$                        | ,<br>(T, S )                     | 0.1514<br><b>0.0022</b>   | Z peak,<br>polarized   | <b>0.000015</b>                                       | 4 bunch scheme             | Design experiment                      |
| $M_W$<br>MeV/c <sup>2</sup>     | ,<br>(T, S, U)                   | 80385<br><b>± 15</b>      | Threshold<br>(161 GeV) | <b>0.3 MeV</b><br><b>&lt;0.5 MeV</b>                  | E_cal &<br>Statistics      | Backgrounds,<br>QED/EW                 |
| $m_{top}$<br>MeV/c <sup>2</sup> | Input                            | 173340<br><b>± 760</b>    | Threshold scan         | <b>10 MeV</b>   | E_cal &<br>Statistics      | Theory limit<br>at 50 MeV?             |

$\Delta\rho$ :  
 $\varepsilon_1$

$$\Gamma_b = (1 + \Delta\rho) \frac{G_F m_Z^3}{24\pi\sqrt{2}} \left( 1 + \left( \frac{g_{ve}}{g_{Ae}} \right)^2 \right) \left( 1 + \frac{3}{4}\frac{\alpha}{\pi} \right)$$

$\varepsilon_3$

$$\sin^2\theta_w^{\text{eff}} \cos^2\theta_w^{\text{eff}} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2} G_F m_Z^2} \frac{1}{1 + \Delta\rho} \frac{1}{1 - \frac{\varepsilon_3}{\cos^2\theta_w}}$$

$\delta_{vb}$

$$\Gamma_b = (1 + \delta_{vb}) \Gamma_d \left( 1 - \frac{\text{mass corrections}}{\alpha m_b^2/M_Z^2} \right)$$

$\varepsilon_2$

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2} G_F \sin^2\theta_w^{\text{eff}}} \cdot \frac{1}{(1 - \varepsilon_3 + \varepsilon_2)}$$

$\sin^2\theta_w^{\text{eff}}$  is defined from

$$\sin^2\theta_w^{\text{eff}} = \frac{1}{4} \left( 1 - \underbrace{\frac{g_{ve}}{g_{Ae}}} \right) = \sin^2\theta_w^{\text{eff}}_{\text{pert}}$$

obtained from asymmetries at the Z.

also

$\Delta z$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2} G_F} \cdot \frac{1}{\left( 1 - \frac{M_W^2}{M_Z^2} \right)} \cdot \frac{1}{(1 - \Delta z)}$$

$$\Delta z = \Delta\alpha - \frac{\cos^2\theta_w}{\sin^2\theta_w} \Delta\rho + 2 \frac{G_F^2\theta_w}{\sin^2\theta_w} \varepsilon_3 + \frac{c^2 - s^2}{s^2} \varepsilon_2$$

## EWRCs

relations to the well measured

$$G_F m_Z \alpha_{\text{QED}}$$

at first order:

$$\Delta\rho = \alpha/\pi \ (m_{\text{top}}/m_Z)^2$$

-  $\alpha/4\pi \ \log(m_h/m_Z)^2$

$$\varepsilon_3 = \cos^2\theta_w \alpha/9\pi \ \log(m_h/m_Z)^2$$

$$\delta_{vb} = 20/13 \alpha/\pi \ (m_{\text{top}}/m_Z)^2$$

complete formulae at 2d order  
including strong corrections  
are available in fitting codes

e.g. ZFITTER, GFITTER

# The main players

## Inputs:

|  |                     |                    |
|--|---------------------|--------------------|
| $G_F = 1.1663787(6) \times 10^{-5} / \text{GeV}^2$ | from muon life time | $6 \cdot 10^{-7}$  |
| $M_Z = 91.1876 \pm 0.0021 \text{ GeV}$             | Z line shape        | $2 \cdot 10^{-5}$  |
| $\alpha = 1/137.035999074(44)$                     | electron g-2        | $3 \cdot 10^{-10}$ |

## EW observables sensitive to new physics:

|   |                       |                   |
|---|-----------------------|-------------------|
| $M_W = 80.385 \pm 0.015$                      | LEP, Tevatron         | $2 \cdot 10^{-4}$ |
| $\sin^2 w^{\text{eff}} = 0.23153 \pm 0.00016$ | WA Z pole asymmetries | $7 \cdot 10^{-4}$ |
| + Rb etc...                                   |                       |                   |

## Nuisance parameters:

|  |  |                     |
|--|--|---------------------|
| $(M_Z) = 1/127.944(14)$                        | hadronic corrections<br>to running alpha | $1.1 \cdot 10^{-4}$ |
| $s(M_Z) = 0.1187(17)$                          | strong coupling constant                 | $1.7 \cdot 10^{-3}$ |
| $m_{\text{top}} = 173.34 \pm 0.76 \text{ GeV}$ | from LHC+Tevatron<br>combination         | $4 \cdot 10^{-3}$   |

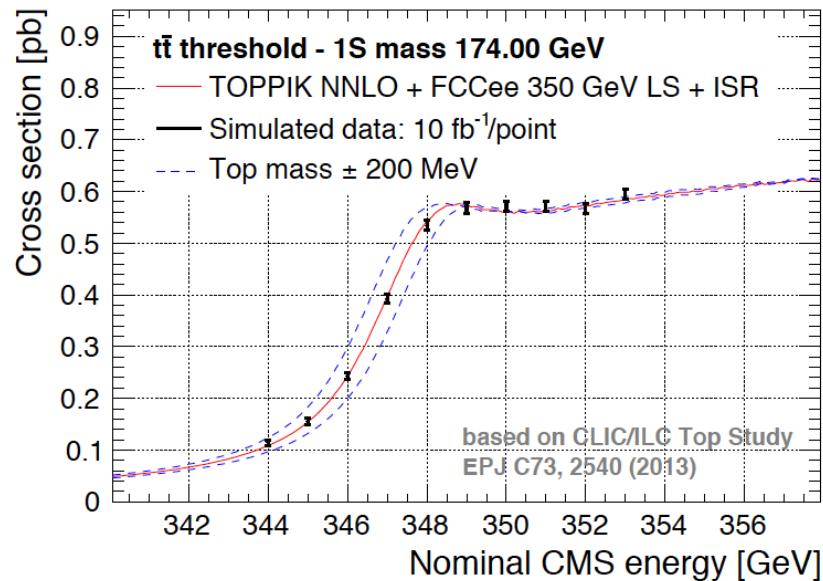
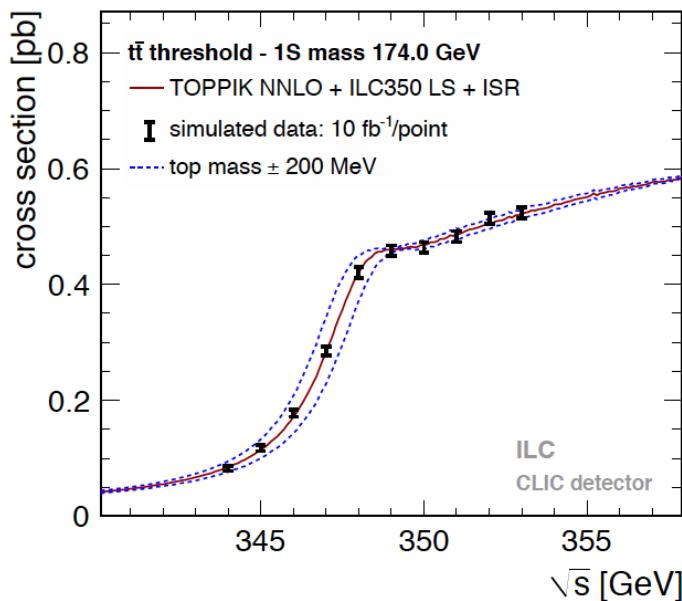
  

|  |                   |
|--|-------------------|
| $m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \text{ GeV}/c^2 \text{ (CMS+ATLAS)}$ | $2 \cdot 10^{-3}$ |
|--|-------------------|

# 350 GeV: the top mass

- Advantage of a very low level of beamstrahlung in circular machines
- Could potentially reach 10 MeV uncertainty (stat) on  $m_{\text{top}}$
- The main issue is relationship between tt threshold and the loop corrections

- Comparing ILC and FCCee - assuming identical detector performance



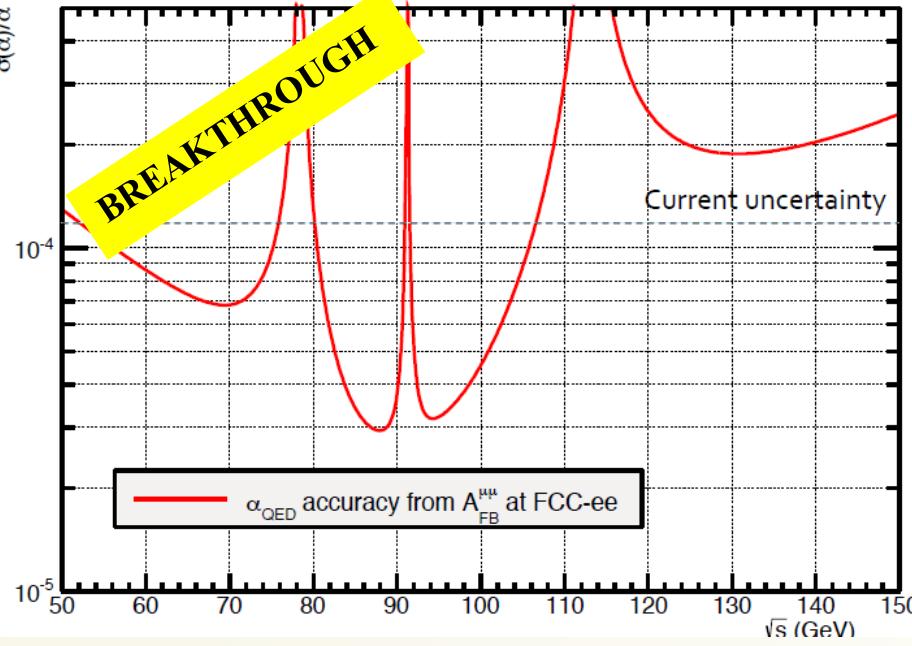
Simulated data points -  
same integrated luminosity

NB: Assuming unpolarized beams - LC  
beams can be polarized, increasing cross-  
sections / reducing backgrounds

$$\sin^2 \theta_w^{\text{eff}} \cos^2 \theta_w^{\text{eff}} = \frac{\pi \alpha(M_Z^2)}{\sqrt{2} G_F M_Z^2}$$

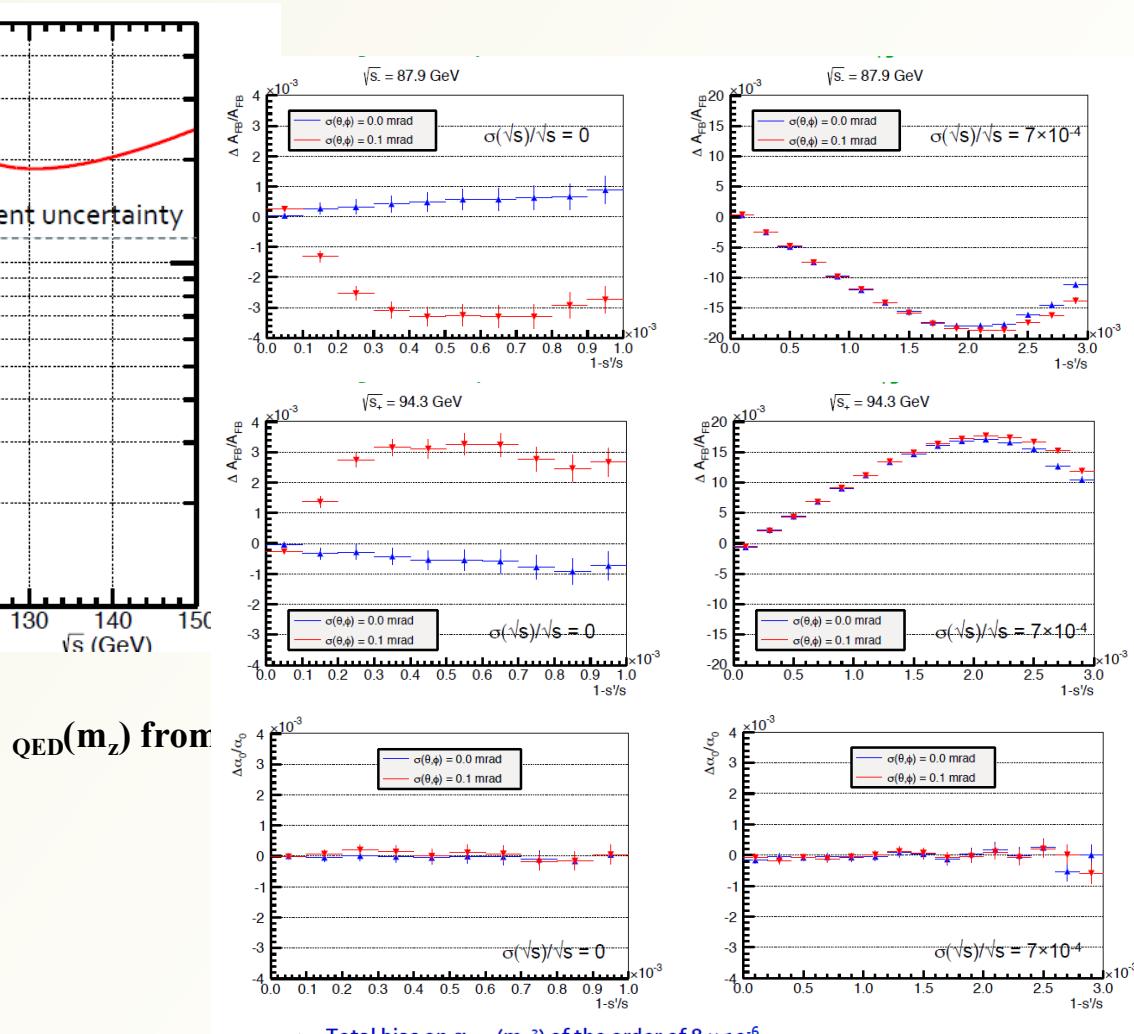
Unwanted error

Physics discoveries



P. Janot discovered that one can measure measuring  $A_{FB}$  at  $\pm 3$  GeV from the Z peak. (Nice Z lineshape scan)

Further studies with S. Jadach shows error cancellation of  $+3$  vs  $-3$  points.



# Strong coupling constant, $\alpha_s(m_Z)$

At LEP, a precise  $\alpha_s(m_Z)$  measurement was derived from the Z decay ratio  $R_I = \Gamma_{\text{had}}/\Gamma_I$ . Reinterpreting this measurement in light of: i) new N<sub>3</sub>LO calculations; ii) improved  $m_{\text{top}}$ ; and iii) knowledge of the  $m_{\text{Higgs}}$ , the uncertainty is now something like:

$$\delta (\alpha_s(m_Z))_{\text{LEP}} = \pm 0.0038 \text{ (exp.)} \pm 0.0002 \text{ (others)}$$

$R_I$  measurement was statistics dominated: Foresee a factor  $\geq 25$  improvement at FCC-ee. From the Z-pole, therefore a reasonable experimental target is

$$\delta (\alpha_s(m_Z))_{\text{FCC-ee}} = \pm 0.00015$$

Similarly, from the WW threshold,  $\alpha_s(m_W)$  can be derived from the high stats measurement of  $B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$

$$\delta (\alpha_s(m_W))_{\text{FCC-ee}} = \pm 0.00015$$

Combining the two above, a realistic target precision would be

$$\delta (\alpha_s(m_Z))_{\text{FCC-ee}} = \pm 0.0001$$

Present W.A.

$$\alpha_s(M_Z) = 0.1181 \pm 0.0013$$

D. Enterria

Workshop on  $\alpha_s$  sept 2015  
D. d'Enterria, P.Z. Skands (eds.)  
arXiv:1512.05194



# Extracting physics from $\sin^2 \text{lept}_W$

## 1. Direct comparison with $m_Z$

$$\sin^2 \theta_w^{\text{eff}} \cos^2 \theta_w^{\text{eff}} = \frac{\pi \alpha(M_Z^2)}{\sqrt{2} G_F m_Z^2} \frac{1}{1 + \Delta\rho} \frac{1}{1 - \frac{\epsilon_3}{\cos^2 \theta_w}}$$

Uncertainties in  $m_{\text{top}}$ ,  $(m_z)$ ,  $m_H$ , etc....  
 $\sin^2 \text{lept}_W \sim (m_z)/3 = 10^{-5}$  if we can reduce  $(m_z)$  (see P. Janot)

## 2. Comparison with $m_w/m_Z$

Compare above formula with similar one:

$$\sin^2 w \cos^2 w = \frac{\pi \alpha(M_Z^2)}{\sqrt{2} G_F m_Z^2} \cdot \frac{1}{\left( -\frac{\cos^2 \theta_w}{\sin^2 \theta_w} \Delta\rho + 2 \frac{G_F \theta_w}{\sin^2 \theta_w} \epsilon_3 + \frac{c^2 - s^2}{s^2} \epsilon_2 \right)}$$

Where it can be seen that  $(m_z)$  cancels in the relation.

The limiting error is the error on  $m_w$ .

For  $m_w = 0.5 \text{ MeV}$  this corresponds to  $\sin^2 \text{lept}_W = 10^{-5}$

Alain Blondel precision measurements at lepton colliders



|                                  | $A_{FB}$ @ FCC-ee   |                       | $A_{LR}$ @ ILC      |
|----------------------------------|---------------------|-----------------------|---------------------|
| visible Z decays                 | $10^{12}$           | visible Z decays      | $10^9$              |
| muon pairs                       | $5 \cdot 10^{10}$   | beam polarization     | 90%                 |
| $A_{FB}$ (stat)                  | $4.6 \cdot 10^{-6}$ | $A_{LR}$ (stat)       | $4.2 \cdot 10^{-5}$ |
| $E_{cm}$ (MeV)                   | 0.1                 |                       | 2.2                 |
| $A_{FB}$ ( $E_{CM}$ )            | $9.2 \cdot 10^{-6}$ | $A_{LR}$ ( $E_{CM}$ ) | $4.1 \cdot 10^{-5}$ |
| $A_{FB}$                         | $1.0 \cdot 10^{-5}$ | $A_{LR}$              | $5.9 \cdot 10^{-5}$ |
| $\sin^2 \theta_W^{\text{ lept}}$ | $5.9 \cdot 10^{-6}$ |                       | $7.5 \cdot 10^{-6}$ |

### PRESENT:

|                                  | from $A_{FB}$ | LEP $2 \cdot 10^7 Z$ | SLC, $5 \cdot 10^5 Z$ | W.A.                |                     |
|----------------------------------|---------------|----------------------|-----------------------|---------------------|---------------------|
| $\sin^2 \theta_W^{\text{ lept}}$ |               | $5.3 \cdot 10^{-4}$  | $2.6 \cdot 10^{-4}$   | $1.6 \cdot 10^{-4}$ | $3.5 \cdot 10^{-5}$ |

from  $QED(mZ) = 0.00002$   
 $\Rightarrow \sin^2 \theta_W^{\text{ lept}} = 7 \cdot 10^{-6}$

Alain Blondel precision measurements at lepton colliders



## Measured $P_\tau$ vs $\cos\theta_{\tau^-}$

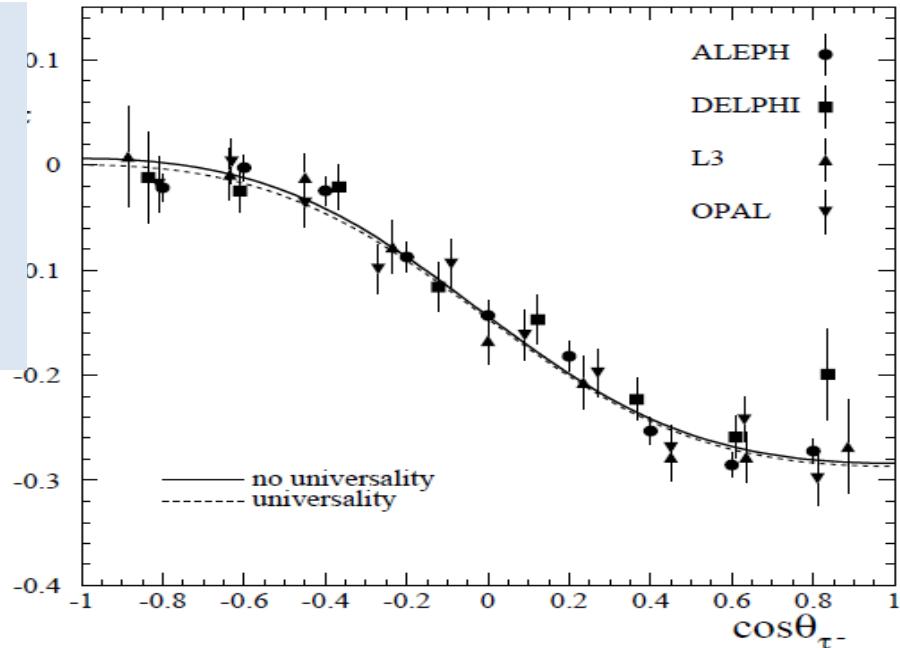


Figure 4.7: The values of  $P_\tau$  as a function of  $\cos\theta_{\tau^-}$  as measured by each of the LEP experiments. Only the statistical errors are shown. The values are not corrected for radiation, interference or pure photon exchange. The solid curve overlays Equation 4.2 for the LEP values of  $\mathcal{A}_\tau$  and  $\mathcal{A}_e$ . The dashed curve overlays Equation 4.2 under the assumption of lepton universality for the LEP value of  $\mathcal{A}_e$ .

|                            | ALEPH                    |                       | DELPHI                   |                       | L3                       |                       | OPAL                     |                       |
|----------------------------|--------------------------|-----------------------|--------------------------|-----------------------|--------------------------|-----------------------|--------------------------|-----------------------|
|                            | $\delta\mathcal{A}_\tau$ | $\delta\mathcal{A}_e$ | $\delta\mathcal{A}_\tau$ | $\delta\mathcal{A}_e$ | $\delta\mathcal{A}_\tau$ | $\delta\mathcal{A}_e$ | $\delta\mathcal{A}_\tau$ | $\delta\mathcal{A}_e$ |
| ZFITTER                    | 0.0002                   | 0.0002                | 0.0002                   | 0.0002                | 0.0002                   | 0.0002                | 0.0002                   | 0.0002                |
| $\tau$ branching fractions | 0.0003                   | 0.0000                | 0.0016                   | 0.0000                | 0.0007                   | 0.0012                | 0.0011                   | 0.0003                |
| two-photon bg              | 0.0000                   | 0.0000                | 0.0005                   | 0.0000                | 0.0007                   | 0.0000                | 0.0000                   | 0.0000                |
| had. decay model           | 0.0012                   | 0.0008                | 0.0010                   | 0.0000                | 0.0010                   | 0.0001                | 0.0025                   | 0.0005                |

Table 4.2: The magnitude of the major common systematic errors on  $\mathcal{A}_\tau$  and  $\mathcal{A}_e$  by category for each of the LEP experiments.



# Theoretical limitations

FCC-ee

*R. Kogler, Moriond EW 2013*

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0002_{m_t} \pm 0.0001_{\alpha_S} \pm 0.0003_{\Delta\alpha_{had}}$$

$$0.0005 \qquad \qquad \qquad M_Z \pm 0.0003_{\Delta\alpha_{had}}$$

$$\pm 0.0001 \qquad \qquad \qquad 2M_H \pm 0.0040_{\text{theo}}$$

$$\sin^2\theta_{\text{eff}}^\ell = 0.231496 \pm 0.0000015_{m_t} \pm 0.0000015_{\alpha_S} \pm 0.0000015_{\Delta\alpha_{had}}$$

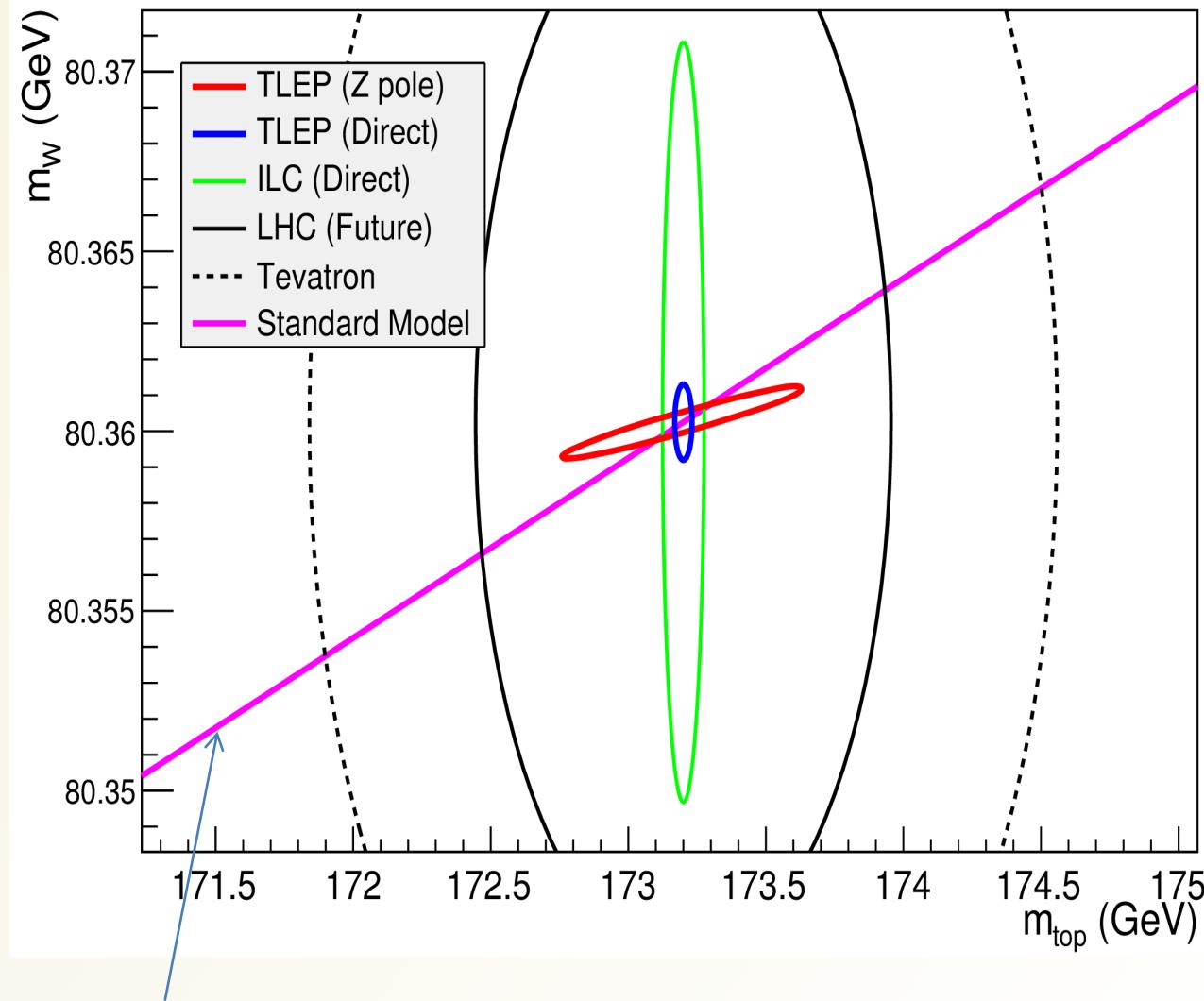
$$0.000001 \qquad \qquad \qquad 5M_Z \pm 0.0000015_{\Delta\alpha_{had}}$$

$$\pm 0.0000014 \qquad \qquad \qquad 2M_H \pm 0.000047_{\text{theo}}.$$

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.  
 BUT can be typically 10 -30 times smaller than present level of theory errors  
Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!  
Suggest including manpower for theoretical calculations in the project cost.



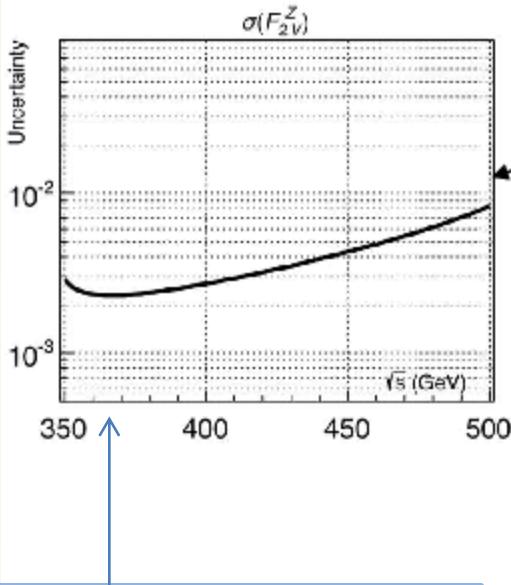


NB width of this line : Z mass error. Without FCC-ee its 2.2 MeV!

in other words ....  $(\quad) = 10^{-5} + \text{several tests of same precision}$

# NEW

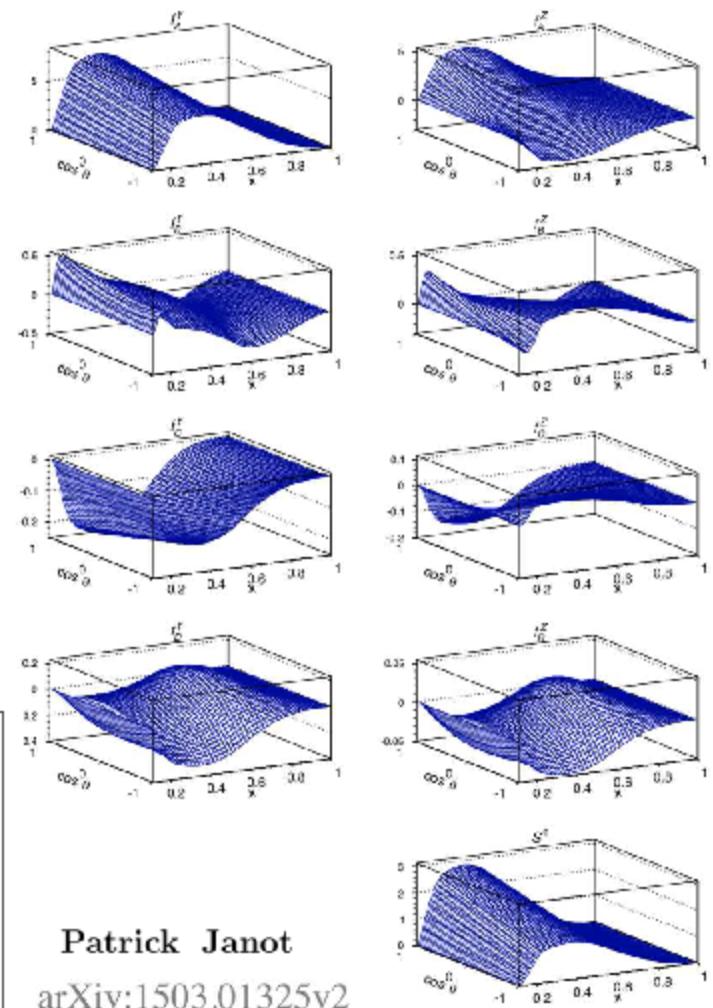
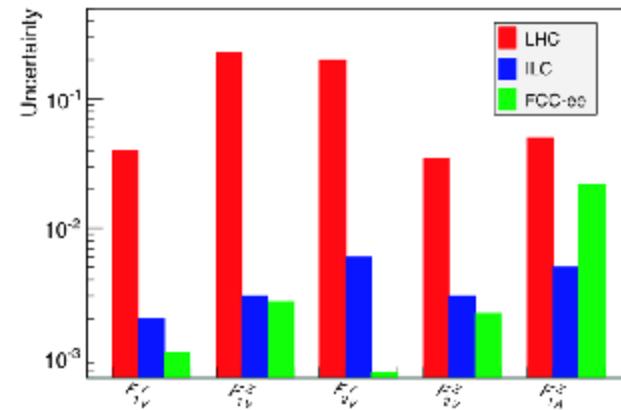
Determination of top-quark EW couplings via measurement of top-quark polarization.  
In semileptonic decays, fit to lepton momentum vs scattering angle



Typically best sensitivity  
just above production  
threshold

Momenta up to: 175 GeV

no need for High Energy  
or beam polarization

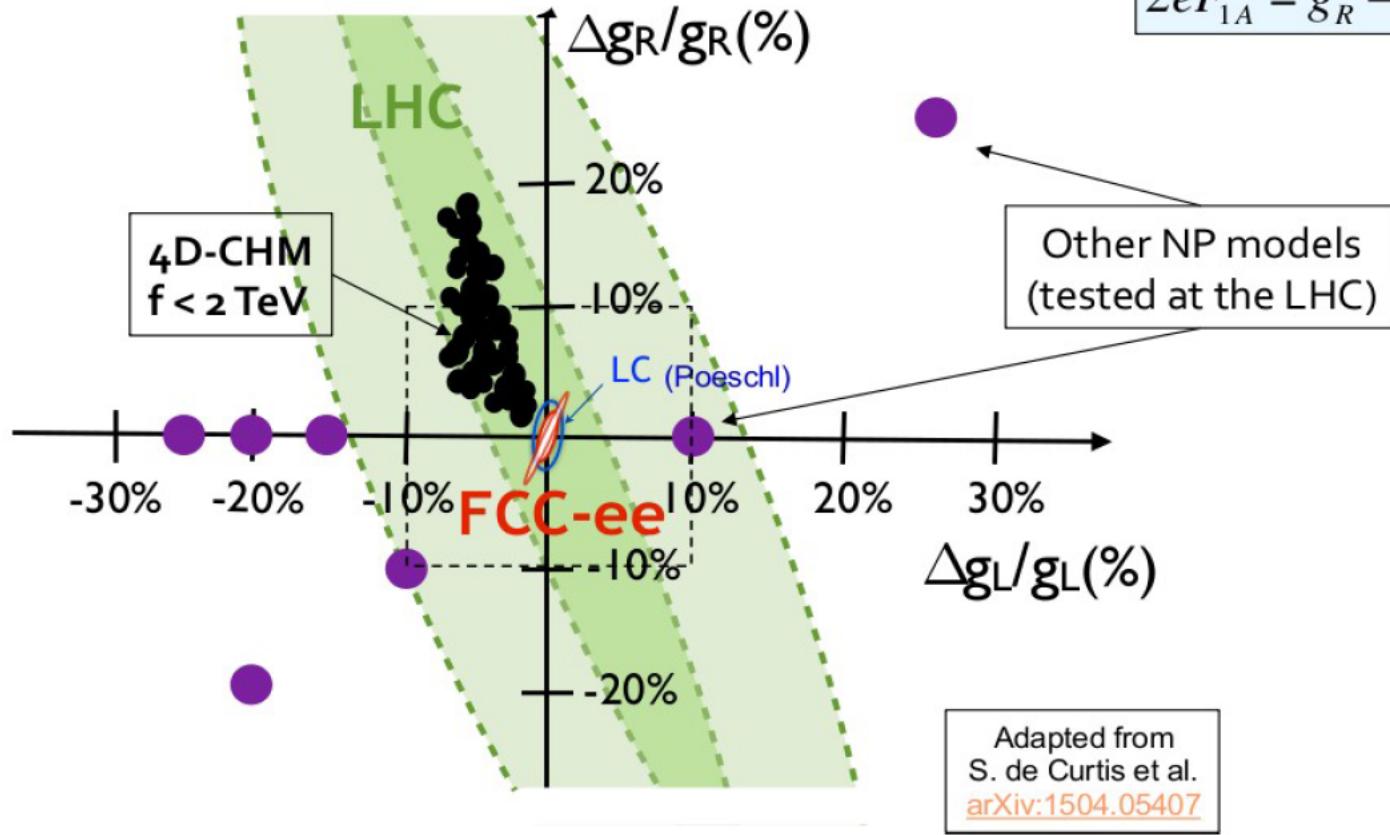


Patrick Janot  
arXiv:1503.01325v2

# FCC-ee sensitivity to new physics: Composite Higgs

- Example:  $t_L t_L Z$  and  $t_R t_R Z$  couplings,  $g_L$  and  $g_R$ 
  - Couplings most sensitive to composite Higgs models

$$2eF_{1V}^Z = g_R + g_L$$
$$2eF_{1A}^Z = g_R - g_L$$



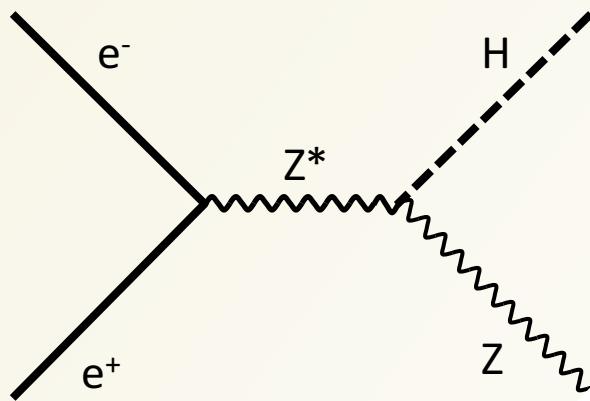
# Higgs production mechanism

“higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold  $\sim 200 \text{ fb}$

$10^{34}/\text{cm}^2/\text{s} \rightarrow 20'000 \text{ Hz events per year.}$  ( $\sim \text{ILC, muon collider}$ )

FCC-ee  $\rightarrow 400'000 \text{ Hz events a year.}$



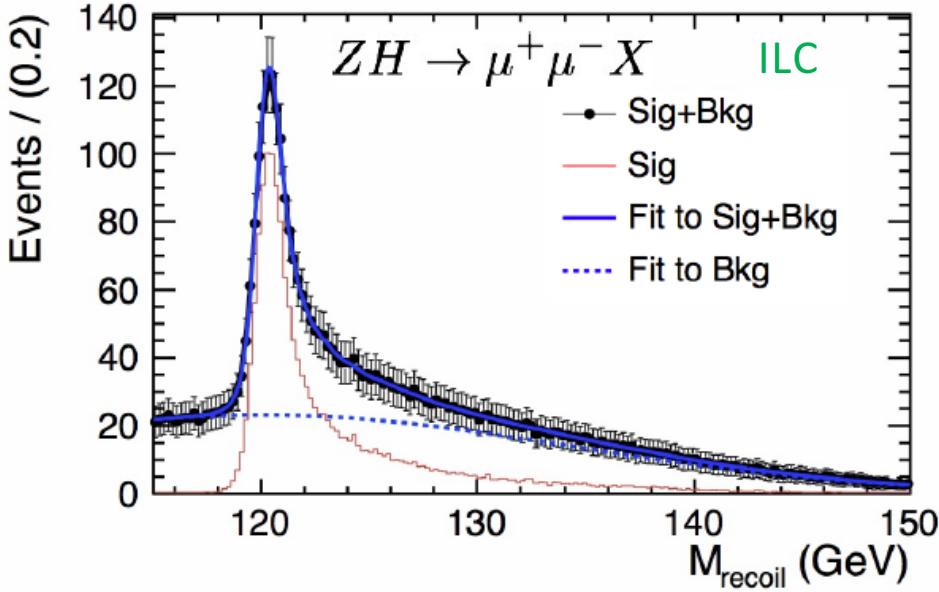
Z – tagging  
by missing mass

For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient

$\rightarrow$  kinematical constraint near threshold for high precision in mass, width, selection  
purity

Alain Blondel precision measurements at lepton colliders





## Z – tagging by missing mass

total rate  $g_{HZZ}^{-2}$

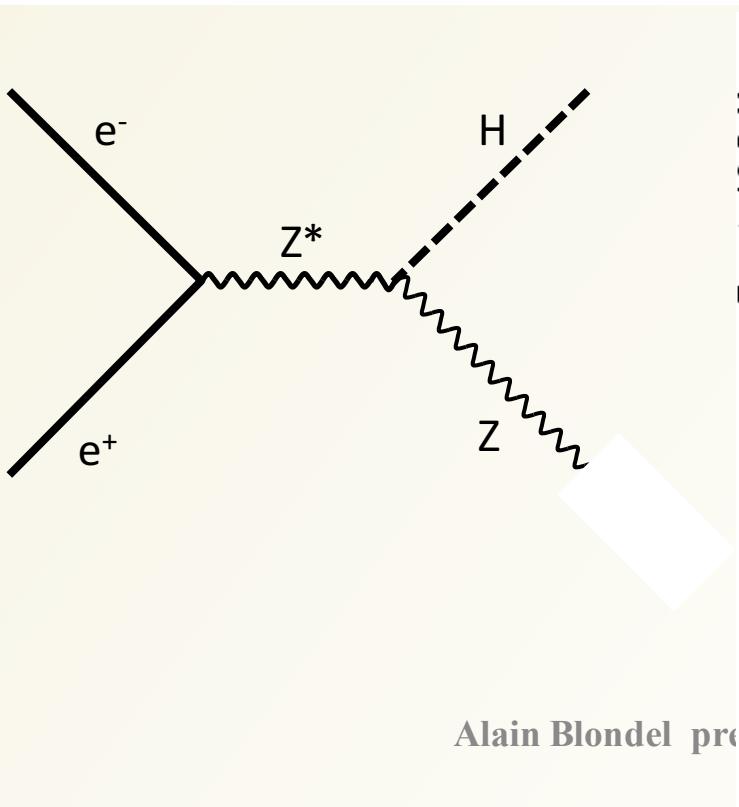
ZZZ final state  $g_{HZZ}^{-4}/\Gamma_H$

→ measure total width  $\Gamma_H$

empty recoil = invisible width

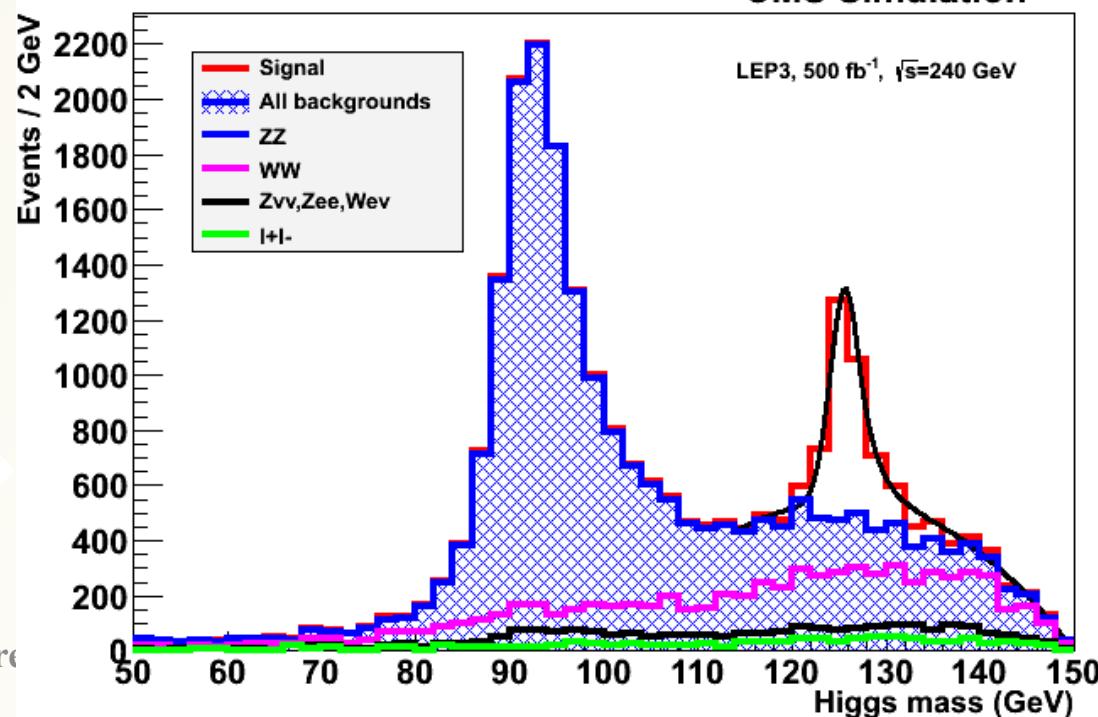
‘funny recoil’ = exotic Higgs decay

easy control below threshold



$Z \rightarrow l+l-$  with  $H \rightarrow \text{anything}$

CMS Simulation



# Higgs Coupling Summary

M. Klute LCWS2015

| Uncertainties           | HL-LHC* | $\mu$ - | CLIC | ILC** | CEPC | FCC-ee | FCC-hh |
|-------------------------|---------|---------|------|-------|------|--------|--------|
| $m_H$ [MeV]             | 40      | 0.06    | 40   | 30    | 5.5  | 8      |        |
| $\Gamma_H$ [MeV]        | -       | 0.17    | 0.16 | 0.16  | 0.12 | 0.04   |        |
| $g_{HZZ}$ [%]           | 2.0     | -       | 1.0  | 0.6   | 0.25 | 0.15   |        |
| $g_{HWW}$ [%]           | 2.0     | 2.2     | 1.0  | 0.8   | 1.2  | 0.2    |        |
| $g_{Hbb}$ [%]           | 4.0     | 2.3     | 1.0  | 1.5   | 1.3  | 0.4    |        |
| $g_{H\tau\tau}$ [%]     | 2.0     | 5       | 2.0  | 1.9   | 1.4  | 0.5    |        |
| $g_{H\gamma\gamma}$ [%] | 2.0     | 10      | 6.0  | 7.8   | 4.7  | 1.5    |        |
| $g_{Hcc}$ [%]           | -       | -       | 2.0  | 2.7   | 1.7  | 0.7    |        |
| $g_{Hgg}$ [%]           | 3.0     | -       | 2.0  | 2.3   | 1.5  | 0.8    |        |
| $g_{Htt}$ [%]           | 4.0     | -       | 4.5  | 18    | -    | -      | 1      |
| $g_{H\mu\mu}$ [%]       | 4.0     | 2.1     | 8.0  | 20    | 8.6  | 6.2    | 1      |
| $g_{HHH}$ [%]           | 30      | -       | 24   | -     | -    | -      | 5      |
| $g_{Hee}/SM$            |         |         |      |       |      | <2     |        |

\* Estimate for two HL-LHC experiments

\*\* ILC lumi upgrade improves precision by factor 2

For ~10y operation. Lots of "!, \*, ?"

**Every number comes with her own story.**

To be added to such a table: rare decays and CP violation

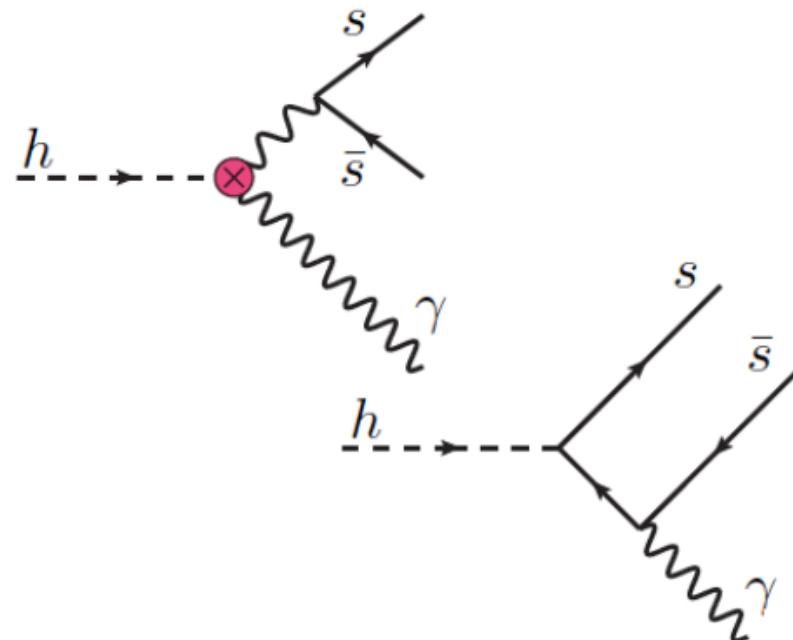


# Exclusive Higgs boson decays

- First and second generation couplings accessible
  - Study of  $\rho\gamma$  channel most promising; expect  $\sim 50$  evts.
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\text{BR}_{h \rightarrow \rho\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$

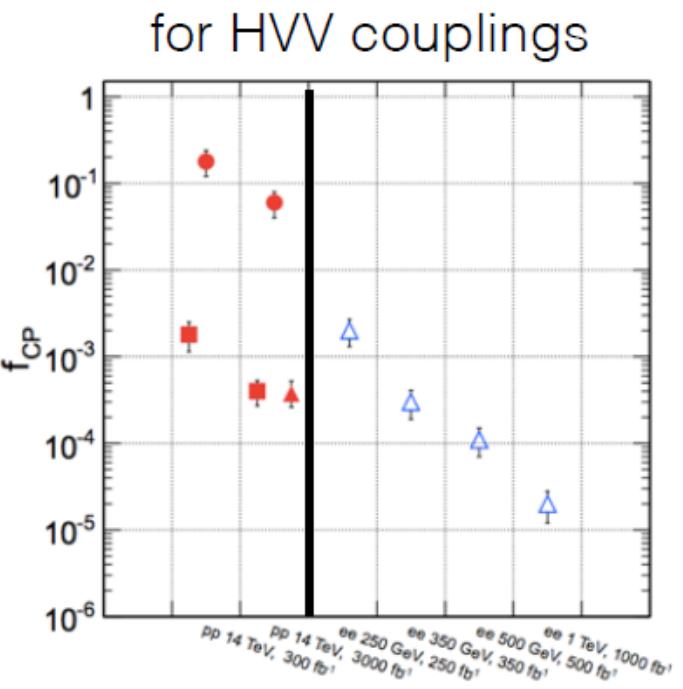
- Also interesting to FCC-hh program
- Alternative  $H \rightarrow MV$  decays should be studied ( $V = \gamma, W$ , and  $Z$ )



- $H \rightarrow J/\Psi \gamma$   $y_c$   
 $H \rightarrow \phi \gamma$   $y_s$   
 $H \rightarrow \rho \gamma$    
 $H \rightarrow \omega \gamma$   $y_u, y_d$

# CP Measurements

- CP violation can be studied by searching for CP-odd contributions; CP-even already established
- Snowmass Higgs paper <http://arxiv.org/abs/1310.8361>
- Higgs to Tau decays of interest
- More detailed presentation by Felix Yu  
<http://arxiv.org/abs/1308.1094>



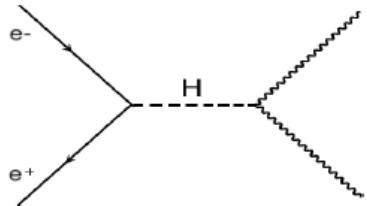
$$\mathcal{L}_{hff} \propto h\bar{f}(\cos \Delta + i\gamma_5 \sin \Delta)f$$

| Colliders    | LHC | HL-LHC | FCCee (1 ab <sup>-1</sup> ) | FCCee (5 ab <sup>-1</sup> ) | FCCee (10 ab <sup>-1</sup> ) |
|--------------|-----|--------|-----------------------------|-----------------------------|------------------------------|
| Accuracy(1σ) | 25° | 8.0°   | 5.5°                        | 2.5°                        | 1.7°                         |

# Electron Yukawa via s-channel $e^+e^- \rightarrow H$ at FCC-ee

[d'Enterria, Wojcik, Aleksan]

- Resonant s-channel Higgs production at  $\sqrt{s} = 125$  GeV has tiny cross sections:

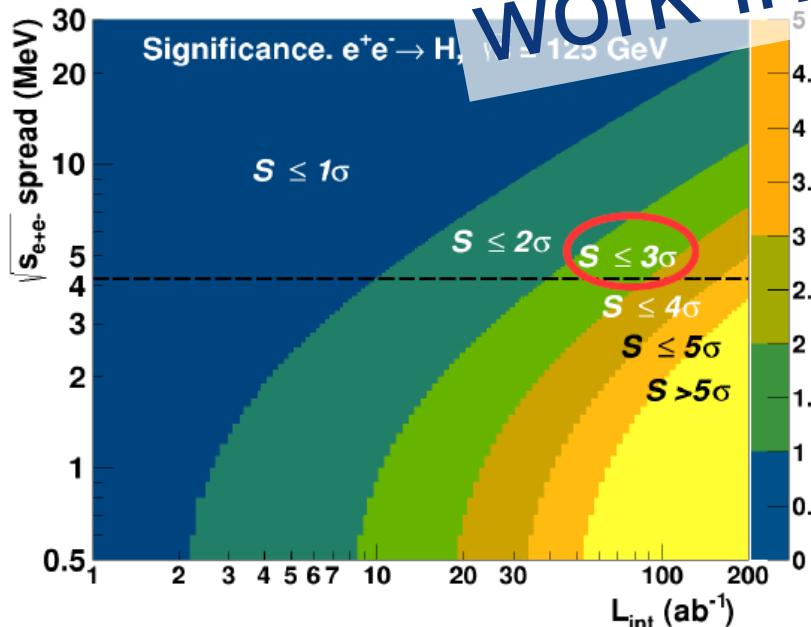


$$\sigma(e^+e^- \rightarrow H)_{\text{Breit-Wigner}} = 1.64 \text{ fb}$$

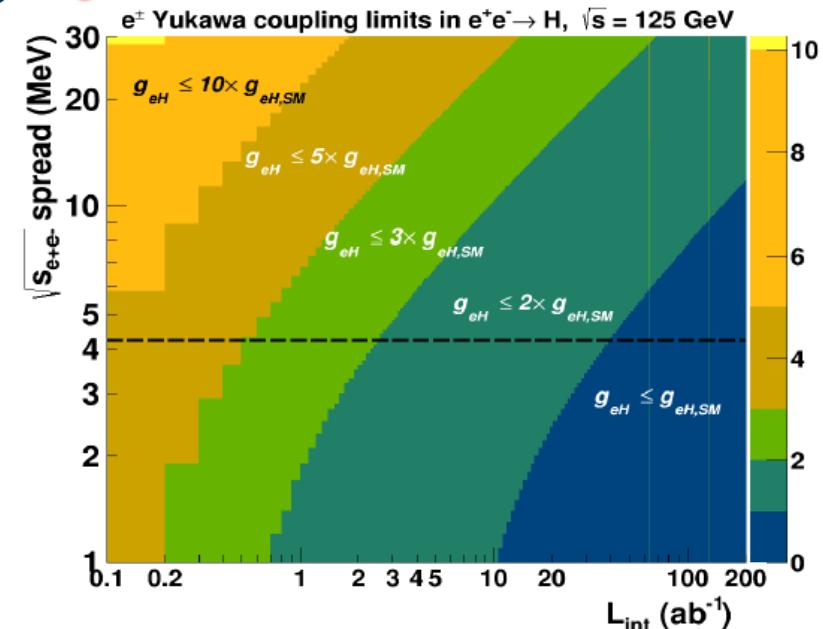
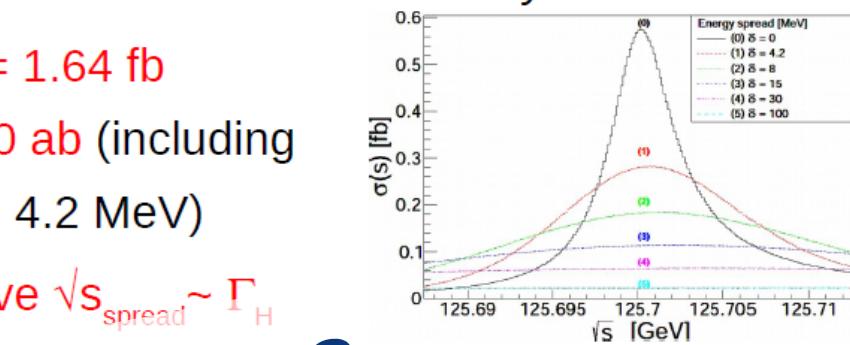
$$\sigma(e^+e^- \rightarrow H)_{\text{visible}} = 290 \text{ ab} \text{ (including ISR + } \sqrt{s}_{\text{spread}} = \Gamma_H = 4.2 \text{ MeV)}$$

Mono-chromatization required to achieve  $\sqrt{s}_{\text{spread}} \sim \Gamma_H$

- Preliminary study for signal + backgrounds in  $10^{14} \text{ fb}^{-1}$  decay channels.
- Significance & limits on e-Yukawa coupling: **work in progress**



3 $\sigma$  observation requires  $L_{\text{int}} = 90 \text{ ab}^{-1}$

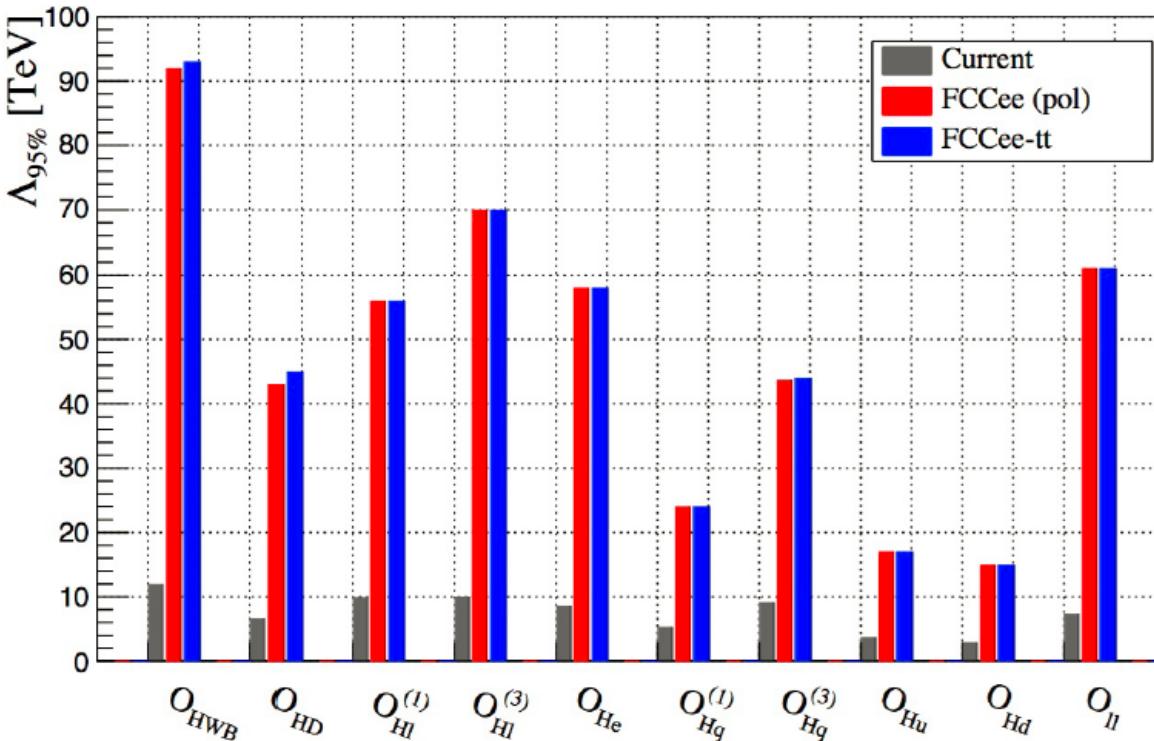


$L_{\text{int}} = 10 \text{ ab}^{-1}$ :  $S \approx 0.7$ ,  $\text{BR}(Hee) < 2.8 \times \text{BR}_{\text{SM}}$   
 $g_{eH} < 1.7 \times g_{eH,SM}$  (95% CL)

## EW LIMITS ON NP: DIMENSION 6 SMEFT

- Dimension six SMEFT: **Present vs. Future**

I operator at a time. Flavor universal.



FCCee: NP scale >15-90 TeV

$$\begin{aligned}
 \mathcal{O}_{Hl}^{(3)} & (H^\dagger i D_\mu^a H) (l_L \gamma^\mu \sigma_a l_R) \\
 \mathcal{O}_{He} & (H^\dagger i D_\mu^a H) (\bar{e}_R \gamma^\mu e_R) \\
 \mathcal{O}_{Hq}^{(1)} & (H^\dagger i \overset{\leftrightarrow}{D}_\mu H) (\bar{q}_L \gamma^\mu q_L) \\
 \mathcal{O}_{Hq}^{(3)} & (H^\dagger i \overset{\leftrightarrow}{D}_\mu^a H) (\bar{q}_L \gamma^\mu \sigma_a q_L) \\
 \mathcal{O}_{Hu} & (H^\dagger i \overset{\leftrightarrow}{D}_\mu H) (\bar{u}_R \gamma^\mu u_R) \\
 \mathcal{O}_{Hd} & (H^\dagger i \overset{\leftrightarrow}{D}_\mu H) (\bar{d}_R \gamma^\mu d_R) \\
 \mathcal{O}_{ll} & (\bar{l} \gamma_\mu l) (\bar{l} \gamma^\mu l)
 \end{aligned}$$

**An example of rare Z decay**

## THE STANDARD MODEL IS COMPLETE .....

but... at least 3 pieces are still missing!

| Three Generations of Matter (Fermions) spin $\frac{1}{2}$ |                                      |                                    |                                    |  |  |
|---|--------------------------------------|------------------------------------|------------------------------------|--|--|
|   | I                                    | II                                 | III                                |  |  |
| mass →  | 2.4 MeV                              | 1.27 GeV                           | 173.2 GeV                          |  |  |
| charge →  | $\frac{2}{3}$                        | $\frac{2}{3}$                      | $\frac{2}{3}$                      |  |  |
| name →  | u<br>Left<br>up                      | c<br>Left<br>charm                 | t<br>Left<br>top                   |  |  |
| Quarks  | d<br>Left<br>down                    | s<br>Left<br>strange               | b<br>Left<br>bottom                |  |  |
| Leptons   | $\nu_e$<br>Left<br>electron neutrino | $\nu_\mu$<br>Left<br>muon neutrino | $\nu_\tau$<br>Left<br>tau neutrino |  |  |
|   | 0.511 MeV                            | 105.7 MeV                          | 1.777 GeV                          |  |  |
|   | -1                                   | -1                                 | -1                                 |  |  |
|   | e<br>Left<br>electron                | $\mu$<br>Left<br>muon              | $\tau$<br>Left<br>tau              |  |  |

| Bosons (Forces) spin 1 |          |         |   |   |   |
|------------------------|----------|---------|---|---|---|
| g                      | 0        | 0       | 0 | 0 | 0 |
| gluon                  |          |         |   |   |   |
| $\gamma$               | 0        | 0       | 0 | 0 | 0 |
| photon                 |          |         |   |   |   |
| Z                      | 91.2 GeV | 0       | 0 | 0 | 0 |
| weak force             |          |         |   |   |   |
| H                      | 126 GeV  | 0       | 0 | 0 | 0 |
| Higgs boson            |          |         |   |   |   |
| W                      | 80.4 GeV | $\pm 1$ | 0 | 0 | 0 |
| weak force             |          |         |   |   |   |
| spin 0                 |          |         |   |   |   |

| Three Generations of Matter (Fermions) spin $\frac{1}{2}$ |                                      |                                    |                                    |            |            |
|---|--------------------------------------|------------------------------------|------------------------------------|------------|------------|
|   | I                                    | II                                 | III                                |            |            |
| mass →  | 2.4 MeV                              | 1.27 GeV                           | 173.2 GeV                          |            |            |
| charge →  | $\frac{2}{3}$                        | $\frac{2}{3}$                      | $\frac{2}{3}$                      |            |            |
| name →  | u<br>Left<br>up                      | c<br>Left<br>charm                 | t<br>Left<br>top                   |            |            |
| Quarks  | d<br>Left<br>down                    | s<br>Left<br>strange               | b<br>Left<br>bottom                |            |            |
| Leptons   | $\nu_e$<br>Left<br>electron neutrino | $\nu_\mu$<br>Left<br>muon neutrino | $\nu_\tau$<br>Left<br>tau neutrino |            |            |
|   | 0.511 MeV                            | $\sim 10$ keV                      | $\sim$ GeV                         | $\sim$ GeV | $\sim$ GeV |
|   | -1                                   | -1                                 | -1                                 | -1         | -1         |
|   | e<br>Left<br>electron                | $\mu$<br>Left<br>muon              | $\tau$<br>Left<br>tau              |            |            |
|   | 0.511 MeV                            | 105.7 MeV                          | 1.777 GeV                          |            |            |

| Bosons (Forces) spin 1 |          |         |   |   |   |
|------------------------|----------|---------|---|---|---|
| g                      | 0        | 0       | 0 | 0 | 0 |
| gluon                  |          |         |   |   |   |
| $\gamma$               | 0        | 0       | 0 | 0 | 0 |
| photon                 |          |         |   |   |   |
| Z                      | 91.2 GeV | 0       | 0 | 0 | 0 |
| weak force             |          |         |   |   |   |
| H                      | 126 GeV  | 0       | 0 | 0 | 0 |
| Higgs boson            |          |         |   |   |   |
| W                      | 80.4 GeV | $\pm 1$ | 0 | 0 | 0 |
| weak force             |          |         |   |   |   |
| spin 0                 |          |         |   |   |   |

neutrinos have mass...

and this very probably implies new degrees of freedom

→ Right-Handed, Almost «Sterile» (very small couplings) Neutrinos.  
completely unknown masses (meV to ZeV), nearly impossible to find.

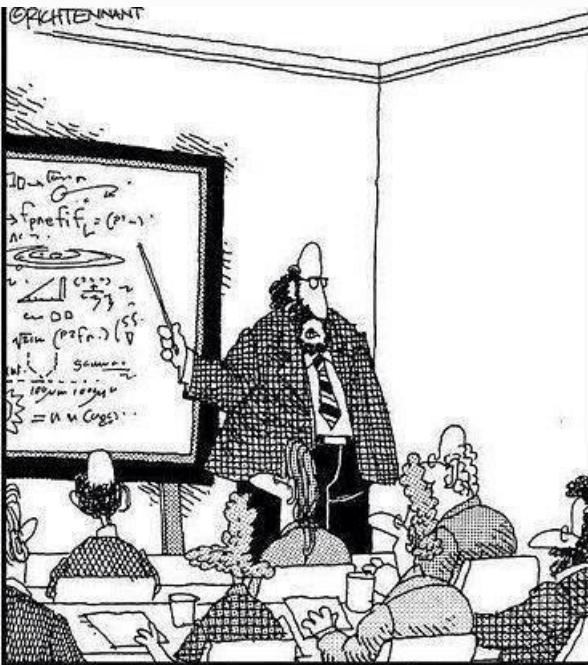
.... but could perhaps explain all: DM, BAU, -masses



# Electroweak eigenstates

|  |  |  |                 |                 |                 |          |
|--|--|--|-----------------|-----------------|-----------------|----------|
| $(\begin{matrix} e \\ \nu_e \end{matrix})_L$ | $(\begin{matrix} \nu \\ \bar{\nu} \end{matrix})_L$ | $(\begin{matrix} \nu \\ \bar{\nu} \end{matrix})_L$ | $(e)_R$         | $(\bar{\nu})_R$ | $(\bar{\nu})_R$ | $Q = -1$ |
|  |  |  | $(\bar{\nu})_R$ | $(\bar{\nu})_R$ | $(\bar{\nu})_R$ | $Q = 0$  |

$|I| = 1/2$



$|I| = 0$



Right handed neutrinos  
are singlets  
no weak interaction  
no EM interaction  
no strong interaction

can't produce them  
can't detect them  
-- so why bother? –

Also called 'sterile'

"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."



# Neutrino Mass eigenstates

See-saw in one family:

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$$\begin{matrix} M_R & 0 \\ m_D & 0 \end{matrix}$$

Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2m_D}{M_R - 0} \ll 1$$

$$m_\nu = \frac{1}{2} \left[ (0 + M_R) - \sqrt{(0 - M_R)^2 + 4m_D^2} \right] \simeq -m_D^2/M_R$$

$$M = \frac{1}{2} \left[ (0 + M_R) + \sqrt{(0 - M_R)^2 + 4m_D^2} \right] \simeq M_R$$

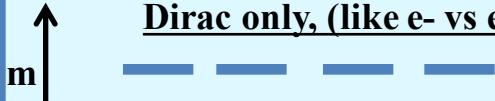
general formula

if  $m_D \ll M_R$

$$M_R = 0$$

$$m_D = 0$$

Dirac only, (like e- vs e+):



$$I_{\text{weak}} = \begin{matrix} L & R & R & L \end{matrix}$$

4 states of equal masses

Some have  $I=1/2$  (active)

Some have  $I=0$  (sterile)

$$M_R = 0$$

$$m_D = 0$$

Majorana only



$$I_{\text{weak}} = \begin{matrix} L & R \end{matrix}$$

2 states of equal masses

All have  $I=1/2$  (active)

$$M_R = 0$$

$$m_D = 0$$

Dirac + Majorana



$$I_{\text{weak}} \sim$$

$$\begin{matrix} L & N_R & R & N_L \end{matrix}$$

4 states , 2 mass levels

m1 have  $I=1/2$  (~active)

m2 have  $I=0$  (~sterile)

# Manifestations of right handed neutrinos

one family see-saw:

$$(m_D/M)$$

$$m_\nu \frac{m_D^2}{M}$$

$$m_N M$$

$$|U|^2 = m_\nu / m_N$$

$$\nu = \nu_L \cos - N^c R \sin$$

$$N = N_R \cos + \nu_L^c \sin$$

what is produced in W, Z decays is:

$$\nu_L = \nu \cos + N \sin$$

$\nu$  = light mass eigenstate  
N = heavy mass eigenstate  
 $\nu_L$ , active neutrino  
which couples to weak interactions  
and  $N_R$ , which does'nt.

- mixing with active neutrinos leads to various observable consequences
  - if very light (eV), possible effect on neutrino oscillations
  - if in keV region (dark matter), monochromatic photons from galaxies with  $E=m_N/2$
- possibly measurable effects at High Energy
  - If N is heavy it will decay in the detector (not invisible)
    - PMNS matrix unitarity violation and deficit in Z «invisible» width
    - Higgs and Z visible exotic decays  $H \rightarrow i_i$  and  $Z \rightarrow i_i$ ,  $W \rightarrow l_i \bar{l}_i$
    - also in charm and b decays via  $W^* \rightarrow l_i \bar{l}_i$
    - violation of unitarity and lepton universality in Z, W or  $\gamma$  decays
    - etc... etc...
- Couplings are small ( $m_\nu/m_N$ ) (but who knows?) and generally thought to be out of reach of hadron colliders → to be revisited for detached vertices @LHC, HL-LHC, FCC-hh

see recent work arXiv:1411.5230 arXiv:1412.6322v1



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Wine and Cheese seminar, Fermilab, 10 June 2016



# Direct RHASnu's production in Z decays

Production:

$$BR(Z^0 \rightarrow \nu_m \bar{\nu}) = BR(Z^0 \rightarrow \nu \bar{\nu}) |U|^2 \left(1 - \frac{m_{\nu_m}^2}{m_{Z^0}^2}\right)^2 \left(1 + \frac{1}{2} \frac{m_{\nu_m}^2}{m_{Z^0}^2}\right)$$

multiply by 2 for anti neutrino and add contributions of 3 neutrino species (with different  $|U|^2$ )

Decay

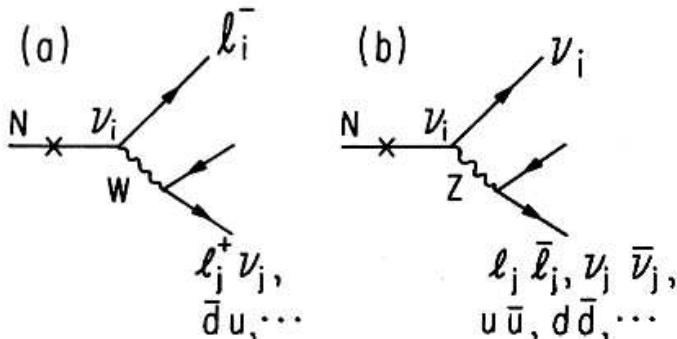


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton  $l_i$  denotes  $e, \mu$ , or  $\tau$ .

Decay length:

$$L \approx \frac{3 \text{ cm}}{|U|^2 (m_{\nu_m}(\text{GeV}/c^2))^6}$$

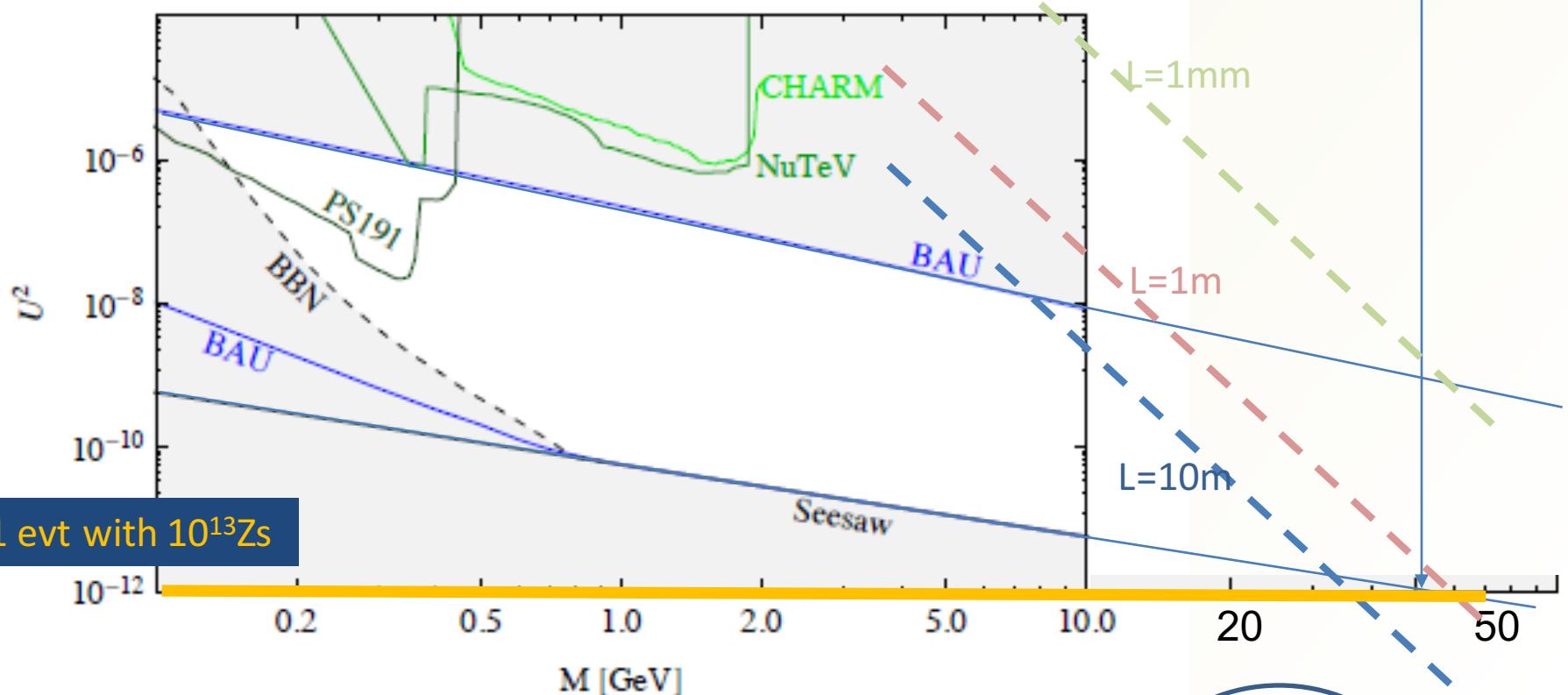
NB CC decay always leads to 2 charged tracks

Backgrounds : four fermion:  $e^+e^- \rightarrow W^{*+} W^{*-}$   $e^+e^- \rightarrow Z^*(vv) + (Z/\ )^*$



# Decay length

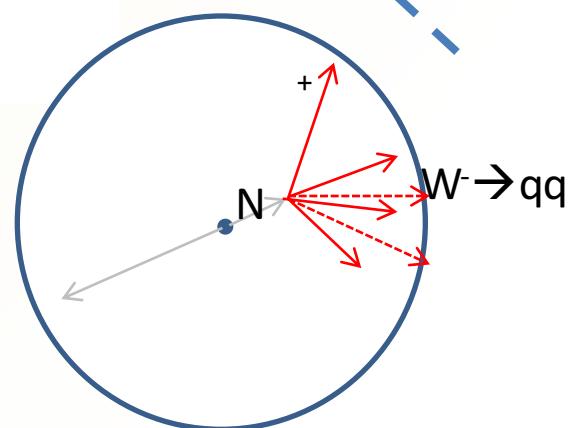
Interesting region  
 $|U|^2 \sim 10^{-9}$  to  $10^{-12}$  @ 50 GeV



heavy neutrino mass  $\sim M$

a large part of the interesting region will lead to detached vertices  
... → very strong reduction of background!

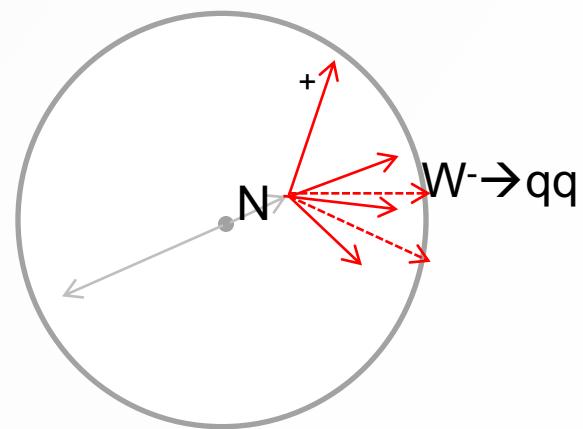
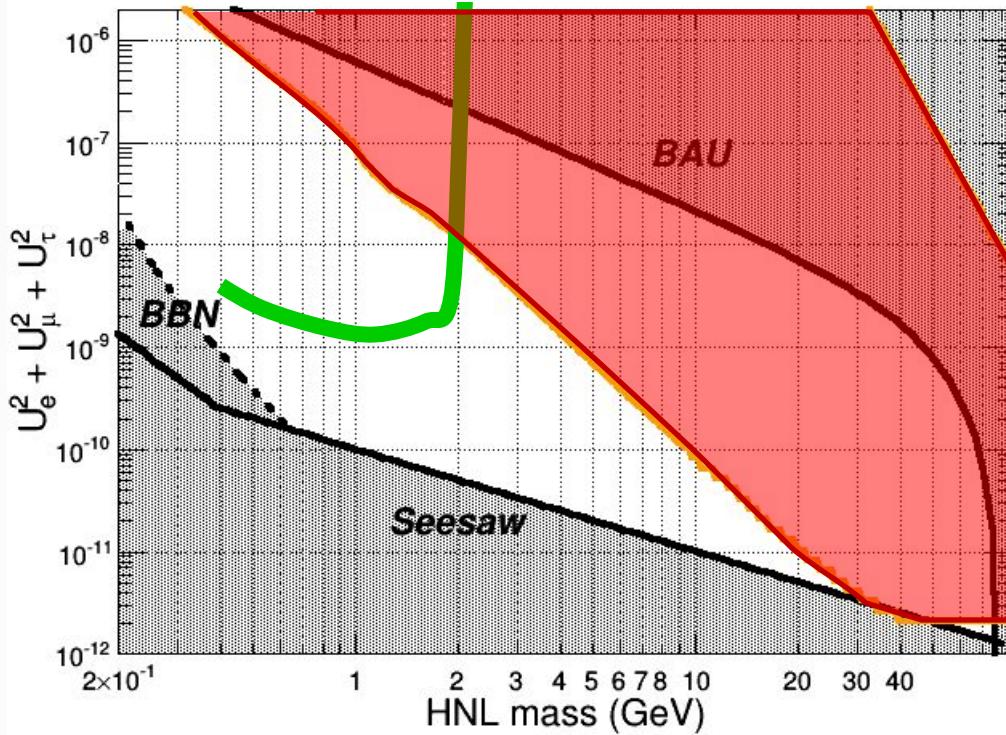
Exact reach domain will depend on detector size  
and details of displaced vertex efficiency & background



# FCC-ee expected sensitivity to heavy RH neutrinos

SHIP

FCC-ee expected sensitivity to Heavy RH neutrino



$$N_Z = 10^{13} \text{ } 100 \text{ m} < L < 5 \text{ m}$$

- region of interest
- FCC-ee sensitivity

NB: very large detector caverns for FCC-hh may allow for very large FCC-ee detector ( $R=15$  m?) leading to improved reach at lower masses



# Summary

- FCC-ee combines several new concepts invented and successfully demonstrated during the last 20 years (LEP2 + flavour-factories)
  - FCC-ee offers extremely high luminosities in the energy range from  $Z$  to  $t\bar{t}$ ; combined w. precise energy calibration at  $Z$  &  $W$ .
  - FCC-ee may serve as spring board for the FCC-hh 100 TeV pp collider, bringing a large tunnel, infrastructure, cryogenics, time, add'l physics motivations + performance goals for FCC-hh
  - FCC-ee technology is ready; ongoing R&D aims at further increasing cost and energy efficiency, making FCC-ee a „green accelerator“ ☺
  - optics fulfils all requirements, matched to FCC-hh footprint, baseline luminosity performance is predicted with confidence, more coming.
- 

- FCC-ee would provide superb discovery potential & a great first step towards 100 TeV. The combination of FCC-ee and FCC-hh is a most powerful combination for the Energy frontier.



Physics at FCC-ee

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Wine and Cheese seminar, Fermilab, 10 June 2016



# FCC International Collaboration

- **75 institutes**
- **26 countries + EC**



Status: 17 April, 2016



# FCC Collaboration Status

75 collaboration members & CERN as host institute, 17 April 2016

ALBA/CELLS, Spain  
Ankara U., Turkey  
U Belgrade, Serbia  
U Bern, Switzerland  
BINP, Russia  
CASE (SUNY/BNL), USA  
CBPF, Brazil  
CEA Grenoble, France  
CEA Saclay, France  
CIEMAT, Spain  
CINVESTAV, Mexico  
CNRS, France  
CNR-SPIN, Italy  
Cockcroft Institute, UK  
U Colima, Mexico  
UCPH Copenhagen, Denmark  
CSIC/IFIC, Spain  
**TU Darmstadt, Germany**  
TU Delft, Netherlands  
**DESY, Germany**  
DOE, Washington, USA  
ESS, Lund, Sweden  
**TU Dresden, Germany**  
Duke U, USA  
EPFL, Switzerland

UT Enschede, Netherlands  
U Geneva, Switzerland  
**Goethe U Frankfurt, Germany**  
**GSI, Germany**  
GWNU, Korea  
U. Guanajuato, Mexico  
Hellenic Open U, Greece  
HEPHY, Austria  
U Houston, USA  
IIT Kanpur, India  
IFJ PAN Krakow, Poland  
INFN, Italy  
INP Minsk, Belarus  
U Iowa, USA  
IPM, Iran  
UC Irvine, USA  
Istanbul Aydin U., Turkey  
JAI, UK  
JINR Dubna, Russia  
Jefferson Lab, USA  
**FZ Jülich, Germany**  
KAIST, Korea  
KEK, Japan  
KIAS, Korea  
King's College London, UK

**KIT Karlsruhe, Germany**  
KU, Seoul, Korea  
Korea U Sejong, Korea  
U Liverpool, UK  
U Lund, Sweden  
MAX IV, Lund, Sweden  
MEPhI, Russia  
UNIMI, Milan, Italy  
MIT, USA  
Northern Illinois U, USA  
NC PHEP Minsk, Belarus  
U Oxford, UK  
PSI, Switzerland  
**U Rostock, Germany**  
RTU, Riga, Latvia  
UC Santa Barbara, USA  
Sapienza/Roma, Italy  
**U Siegen, Germany**  
U Silesia, Poland  
TU Tampere, Finland  
TOBB, Turkey  
U Twente, Netherlands  
TU Vienna, Austria  
Wigner RCP, Budapest, Hungary  
Wroclaw UT, Poland



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# FCC Week 2015

IEEE International Future Circular Collider Conference  
March 23 - 27, 2015 | Washington DC, USA



## First FCC Week Conference Washington DC 23-27 March 2015

<http://cern.ch/fccw2015>

P. Lebrun (CERN)

Further information and registration

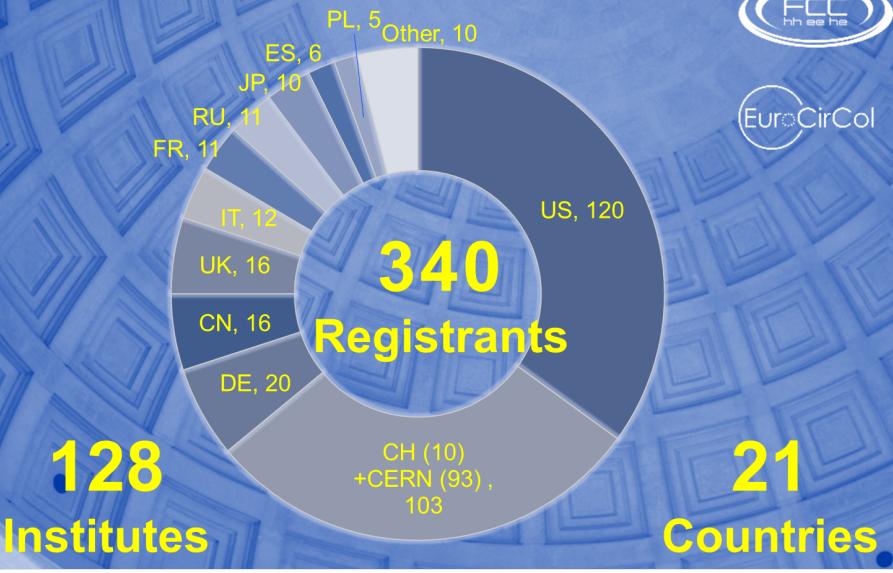
<http://cern.ch/fccw2015>



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Science

## FCC Week 2015 STATISTICS



128  
Institutes



# FCCWEEK 2016

International Future Circular Collider Conference

## ROME 11-15 APRIL

fccw2016.web.cern.ch



<http://cern.ch/fccw2016>

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# FCC Week 2017



**29 May – 2 June 2017  
Berlin, Germany**



# FCC RF & cryo power

|                           | Z                     | W                 | ZH                | ttbar             |
|---------------------------|-----------------------|-------------------|-------------------|-------------------|
| total voltage / beam [GV] | 0.2                   | 0.8               | 3                 | 10                |
| no. cavities / beam       | 75                    | 150               | 400               | 670               |
| RF frequency [MHz]        | 400                   |                   |                   |                   |
| cells / cavity            | 1                     |                   | 2                 |                   |
| cavity length [m]         | 0.38                  | 0.75              | 0.75              | 0.75              |
| $Q_0 [10^9]$              | 3                     | 3                 | 3                 | 3                 |
| material & temperature    | <b>Nb/Cu at 4.5 K</b> |                   |                   |                   |
| gradient [MV/m]           | 7.0                   | 7.1               | 10                | 10                |
| voltage / cavity [MV]     | 2.7                   | 5.3               | 7.5               | 7.5               |
| input power / cavity [MW] | 0.67                  | 0.33              | 0.125             | 0.075             |
| R/Q [ $\Omega$ ] linac    | 87                    |                   | 169               |                   |
| matched $Q_L$             | $1.3 \times 10^5$     | $5.0 \times 10^5$ | $2.7 \times 10^6$ | $4.4 \times 10^6$ |
| HOM loss / cavity [kW]    | 3.1                   | 1.2               | 0.3               | 0.3               |
| dynamic/static cryo power | 1, 1                  | 4, 1              | 20, 3             | 33, 6             |
| total cryo power [MW]     | 2                     | 5                 | 23                | 39                |

## Precise Compton Polarimetry:

- Compton backscattering of  $\sim 515$  nm photons
- circularly polarized photons  $\leftrightarrow$  transverse polarized e-beam
- measurement of shift of photon intensity distribution
- counting silicon microstrip detector with  $p = 50 \mu\text{m}$

## Achievable precision: (bunch by bunch, turn by turn)

- ELSA (3.5 GeV, distance 15 m):  $\Delta P \approx 1\%$
- FCC-ee (< 90 GeV, distance 500 m):  $\Delta P < 0.1\%$
- FCC-ee (175 GeV, distance 500 m):  $\Delta P \approx 0.2\%$

using conventional high power laser

W. Hillert



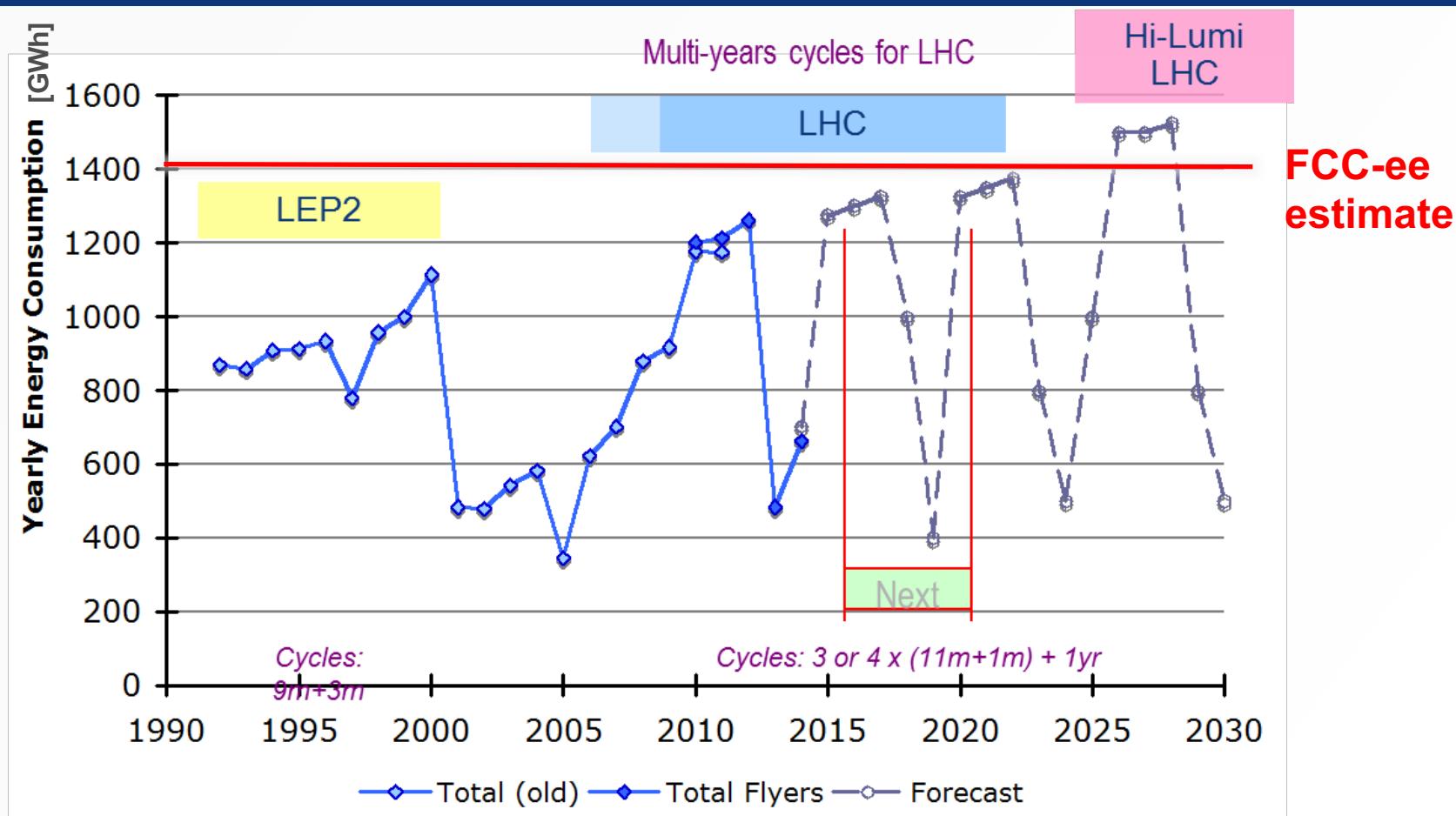
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# CERN energy consumption



S. Claudet - CERN  
Procurement Strategy

3rd Energy Workshop 29-30 October 2015



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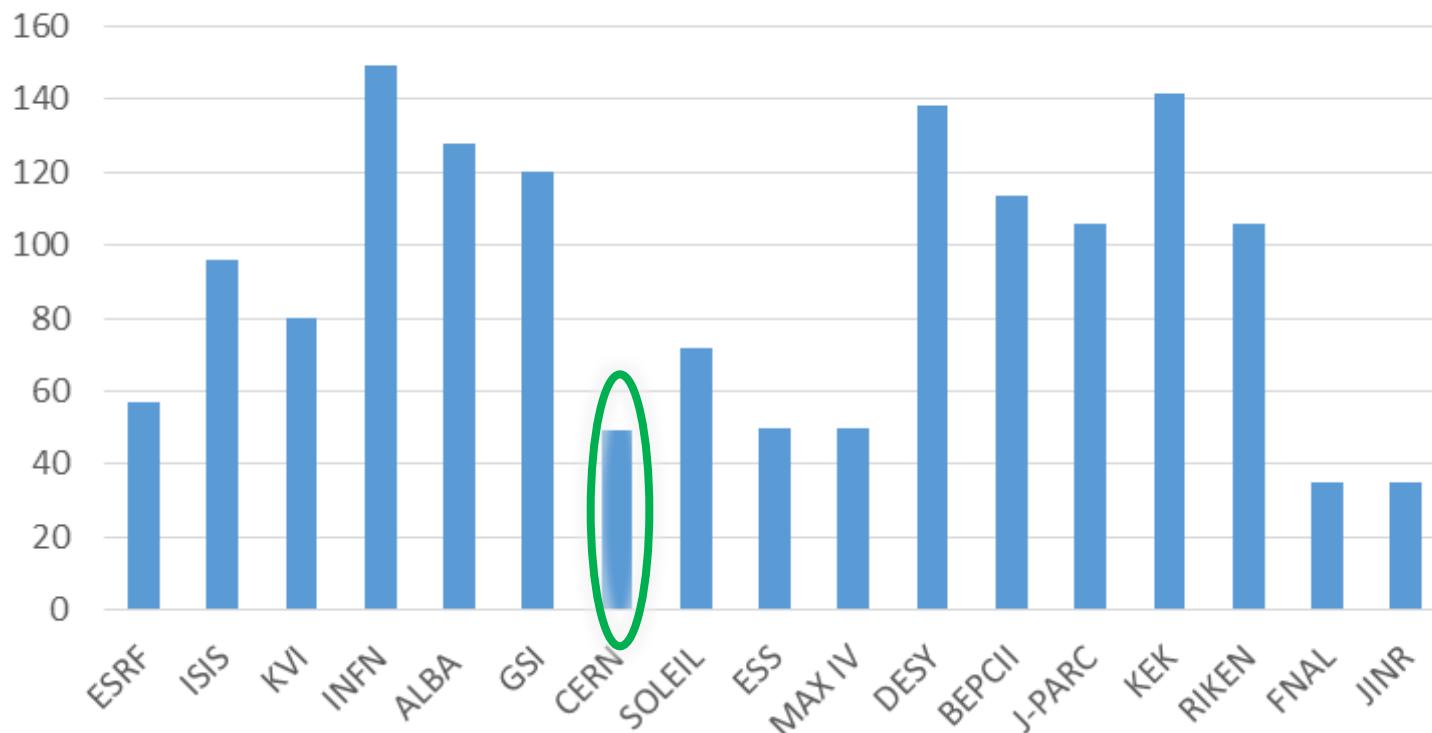
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# electricity cost

facility electricity cost 2014/15 in Euro / MWh

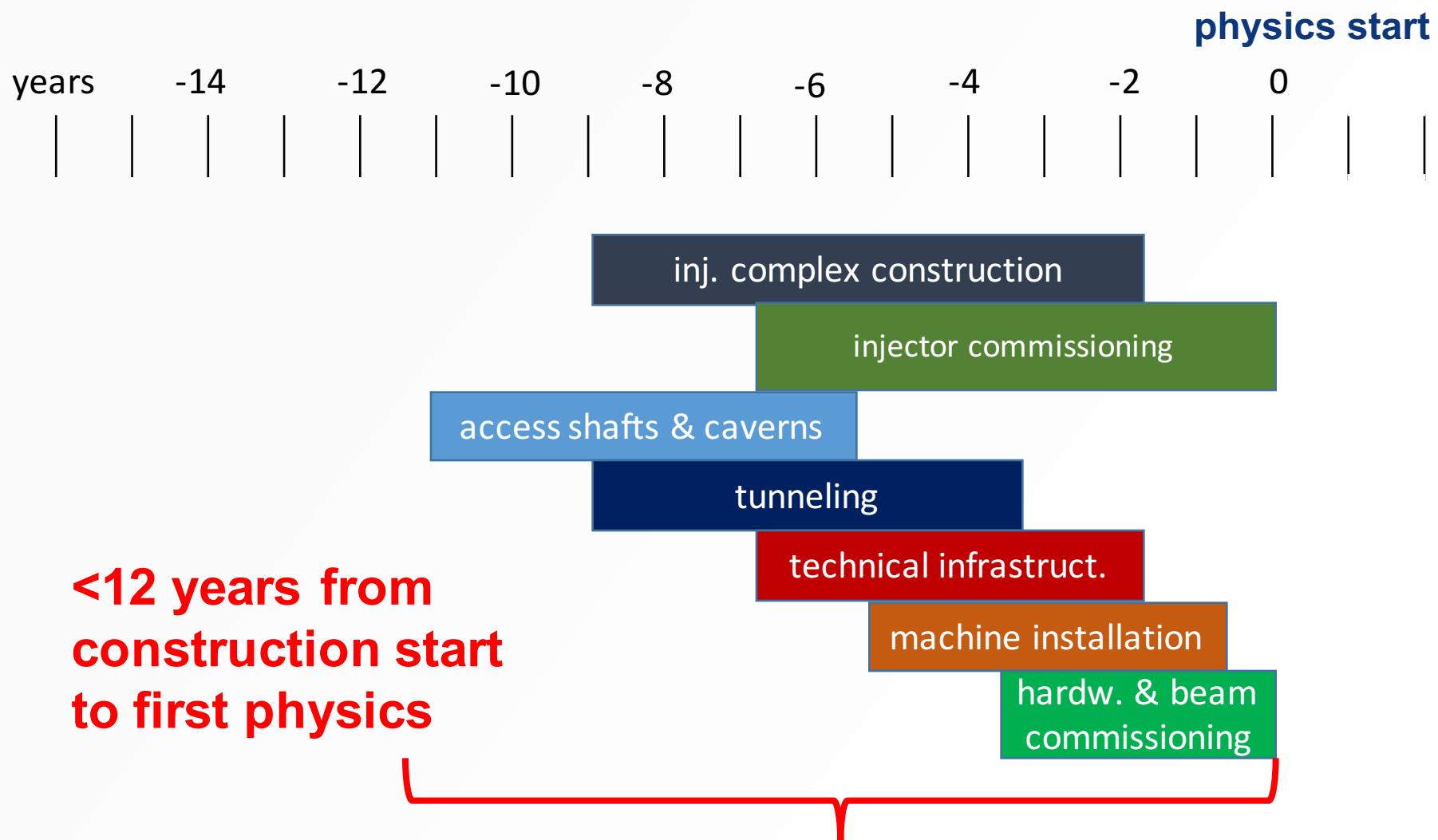


Courtesy: M. Seidel, EuCARD-2, V. Shiltsev, K. Oide, Q. Qin, G. Trubnikov, and others

**1400 GWh / yr → ~70 MEuro / yr**

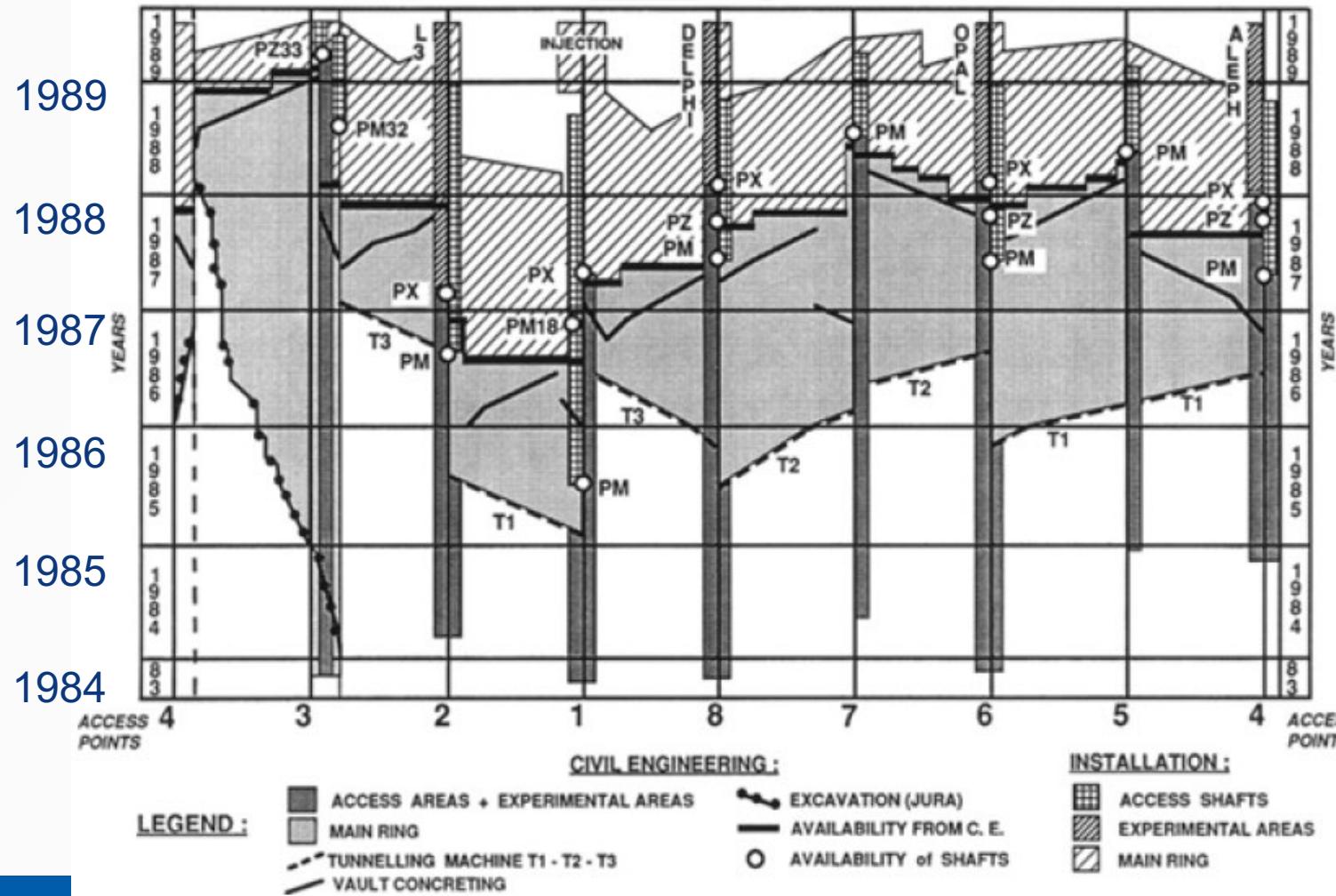


# tentative preliminary time line for FCC-ee construction



# recall the construction of LEP

How it was done



<6 years  
from  
zero  
to  
physics

E. Picasso  
H. Schopper